

## Interseismic deformation above the Sunda Megathrust recorded in coral microatolls of the Mentawai islands, West Sumatra

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Received 15 April 2006; revised 28 August 2006; accepted 9 October 2006; published 27 February 2007.

[1] The geomorphology and internal stratigraphy of modern coral microatolls show that all the outer arc Mentawai islands of West Sumatra have been subsiding over the past several decades. These same islands rose as much as 3 m during the giant megathrust earthquakes of 1797 and 1833, and the current subsidence probably reflects strain accumulation that will lead to future large earthquakes. Average subsidence rates over the past half century vary from 2 to 14 mm yr<sup>-1</sup> and increase southwestward, toward the subduction trench. The pattern is consistent with rates of subsidence measured by a sparse network of continuously recording Global Positioning System (cGPS) stations and with locking of a 400-km-long section of the underlying subduction megathrust, between about 1°S and 4°S. This record of subsidence and tilting, extending nearly a century into the past, implies that the region is advancing toward the occurrence of another giant earthquake. However, evidence of episodic rather than steady subsidence reflects a behavior that is more complex than simple elastic strain accumulation and relief. Most prominent of these episodes is an extensive emergence/subsidence couplet in about 1962, which may be the result of rapid, aseismic slip on the megathrust, between the islands and the trench. Lower subsidence rates recorded by the corals since about 1985 may reflect failure on many small patches within the locked section of the megathrust.

**Citation:** Natawidjaja, D. H., K. Sieh, J. Galetzka, B. W. Suwargadi, H. Cheng, R. L. Edwards, and M. Chlieh (2007), Interseismic deformation above the Sunda Megathrust recorded in coral microatolls of the Mentawai islands, West Sumatra, *J. Geophys. Res.*, 112, B02404, doi:10.1029/2006JB004450.

### 1. Introduction

[2] The western half of the 5500-km-long Sunda megathrust presents a unique opportunity to understand the behavior of a major subduction zone through several cycles of strain accumulation and relief. This is because a 2500-km-long chain of islands sits above the shallow portions of the megathrust, from the Andaman islands in the north nearly to the Sunda Strait in the south (Figure 1). The islands are platforms for a wide range of geodetic instruments, from modern GPS stations to coral microatolls, that have been recording strains for decades and even centuries.

[3] Such records are particularly interesting now, in the wake of the two giant earthquakes of 2004 and 2005, caused by rupture of nearly 2000 km of the Sunda megathrust north of the equator [Briggs *et al.*, 2006; Subarya *et al.*, 2006]. During these earthquakes, the outer-arc islands above the shallowest parts of the megathrust rose suddenly, exposing

and thereby killing wide tracts of the fringing reefs. In the decades prior to the earthquakes, coconut groves, rice paddies and other man-made features had been submerging slowly into the intertidal zone, dramatic manifestations of the slow accumulation of strain above the interseismically locked portions of the megathrust (Figures 2a and 2b).

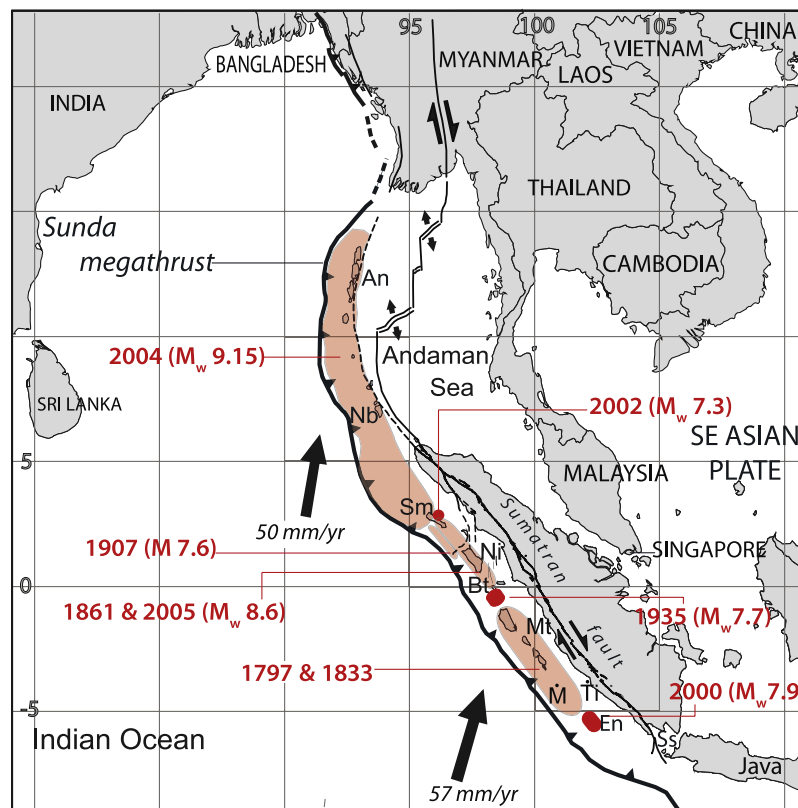
[4] The focus of this paper is south of the equator, where giant earthquakes have not occurred since 1797 and 1833 [Natawidjaja *et al.*, 2006] and where such subsidence continues today. The subsidence is evident along nearly every coastline of the outer-arc Mentawai islands, because the littoral and intertidal reef environments are encroaching into jungles and swamps, drowning and eroding forests, palm groves, roads, villages and other cultural features that were established above high-tide levels (Figures 2c–2e).

[5] In previous papers we have demonstrated the use of coral microatolls to recover sea level histories spanning much of the 20th century on islands of western Sumatra [Natawidjaja *et al.*, 2004; Sieh *et al.*, 1999; Zachariasen *et al.*, 2000]. These papers showed that certain species of the coral genera *Porites* and *Goniastrea* are sensitive natural recorders of lowest tide levels, which makes them ideal natural instruments for measuring emergence or subsidence relative to a tidal datum [Scoffin and Stoddart, 1978; Taylor *et al.*, 1987]. These *Porites* and *Goniastrea* coral heads grow radially upward and outward until they reach an elevation that allows their highest corallites to be exposed

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**Figure 1.** Western half of the Sunda megathrust and its major historical seismic ruptures. A 2500-km-long chain of islands above the megathrust enables measurement of deformations associated with strain accumulation and relief. This paper focuses on the past half century of strain accumulation above the Mentawai (Mt) islands, using the record of submergence of coral microatolls. An, Andaman islands; Nb, Nicobar islands; Sm, Ni, Bt, M, En, and Ti, Simeulue, Nias, Batu, Mega, Enggano, and Tikos islands. Vectors are relative motion of Australian plate relative to Southeast Asian plate.

to the atmosphere during lowest tides. At this highest level of survival (HLS), subaerial exposure kills the uppermost corallites in the colony, which restricts future upward growth. The HLS for *Porites* microatolls is about 40 mm above lowest low tide [Briggs *et al.*, 2006]. *Goniastrea* microatolls can withstand exposure about 100 mm higher.

[6] Thus the coral heads record in their geomorphology and internal stratigraphy the history of lowest low tides. If a reef is subsiding relative to sea level, younger annual bands are able to grow upward to higher levels than older bands. This leads to the formation of a raised outer rim, resembling in form and origin the island atolls first described and explained by Darwin [1842] in the Cocos islands, a thousand kilometers or so to the south. Heads so influenced by sea level are called microatolls.

[7] Our methods for determining sea level histories from microatolls have been described in our earlier papers. An illustrated description of the process appears in Appendix 2 of Natawidjaja *et al.* [2006]. (An animation of coral growth in response to sea level changes is available at <http://es.ucsc.edu/~ward/Srm00A1.mov>). Suffice it to say here that we cut vertical slices from the coral microatolls. We then map the annual banding visible in X rays of these slices to determine the annual growth pattern of the coral head. The highest level of each annual band is, roughly speaking, at or below the elevation of lowest low tide in the year of

the band's formation. In constructing a sea level history from the tops of these annual bands, we take into account erosion and other nontectonic effects on the upper surface of the microatoll [Natawidjaja *et al.*, 2004]. Thus we document the history of the HLS over the decades of growth of the coral head. Since the HLS is a reliable surrogate for annual lowest low tide, we are able to construct a time series of sea level spanning most of the life of the coral.

[8] Natawidjaja *et al.* [2004] used sea level histories from fringing reefs near the equator to show that the megathrust there fails predominantly by aseismic slip. The largest seismic rupture of the past 260 years there [Natawidjaja, 2003, chapter 5] produced a  $M_w$  7.7 earthquake in 1935. In this paper, we describe the sea level histories for 28 sites on the fringing reefs of the Mentawai islands and mainland coast immediately to the south, between latitudes about  $1^\circ$  and  $4^\circ$ S. This section of the megathrust generated large historical earthquakes in 1797 and in 1833 [Natawidjaja *et al.*, 2006; Newcomb and McCann, 1987], and analysis of survey mode GPS data shows that it was storing strain throughout the 1990s [McCaffrey *et al.*, 2000; Prawirodirdjo *et al.*, 1997].

[9] M. Chlieh *et al.* (Geodetic and paleogeodetic resolution of locked patches on the Sunda megathrust, offshore Sumatra, manuscript in preparation, 2006), interpret these data in concert with survey mode and new continuous GPS



**Figure 2.** Aerial views of subsiding coastlines. (a) Grove of dead coconut palm trees near Afulu, west coast of Nias island, in the intertidal zone due to slow subsidence in the decades prior to 2005. Photograph taken January 2005. (b) Same grove standing out of the intertidal zone, following 2.3 m of uplift during the March 2005 Nias-Simeulue earthquake [Briggs *et al.*, 2006]. Photograph taken May 2005. (c) Dead tree trunks in the intertidal zone on the mainland side of the north tip of North Pagai island (see Figure 3 for location). (d) A field of dead snags seaward of the modern beach south of Perak Batu village, northeast coast of South Pagai island. (e) Coconut root balls and boardwalk now seaward of the beach at the Saibi village, central eastern Siberut.

data to understand the depth of locking of the underlying megathrust and the degree to which it is locked.

## 2. Data From Microatolls

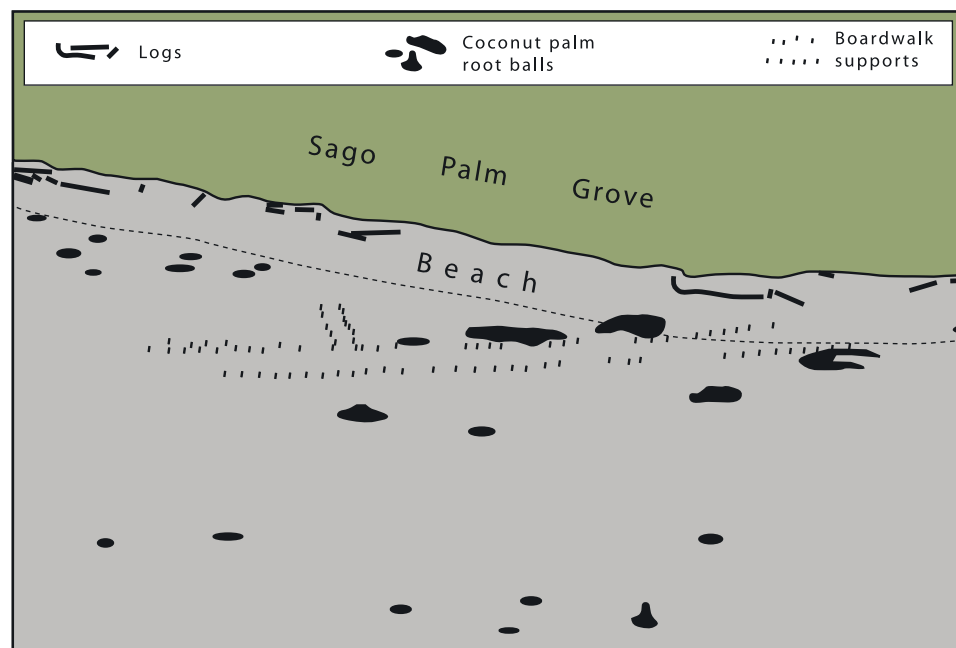
### 2.1. Overview

[10] In 1997, 1999, 2000, 2002, and 2003 we searched the reefs of the Mentawai islands for living microatolls (Figure 3). Only in mid-1997 did we find an abundance of healthy, living heads, for the reefs experienced an extensive die-off in late 1997, coincident with an extensive red tide. The devastation of the reef followed several months of smoke and haze caused by great fires set to clear Kalimantan and east Sumatran forests for the expansion of plantations. Coral death was nearly total in the Batu islands and on Siberut and northern Sipora islands, but the percentage of living heads increased southward through the Pagai islands. The death of most of the living reef in late 1997 made it more difficult to distinguish modern from fossil coral. Even so, we could usually distinguish dead modern

heads from fossil heads by their lesser degree of chemical and bioerosion. In addition, we used U-Th disequilibrium dating to verify young ages. Table 1 lists the U-Th analyses we used to establish the modern ages of corals in this effort.

[11] The gross morphology of the coral heads provides clues to variations in the rate of submergence of the Mentawai reefs. For example, in places where the rate of submergence is significantly less than the potential rate of upward growth of the coral, the upper surfaces of the heads have the cup-shaped microatoll morphology. Where rates of submergence are nearly equal to or greater than the potential rate of upward growth, the microatoll form is not present or is less well expressed, because the heads seldom or never reach the level of lowest low tide. This is commonly the case along the northern coast of Sipora island, the southern coast of Siberut island and among the islets in between. Along coasts where the rate of submergence is relatively low, the aspect ratio of the microatolls gives a rough indication of the rate of submergence [Zachariasen *et al.*, 2000]. In general, lower rates yield microatolls that are





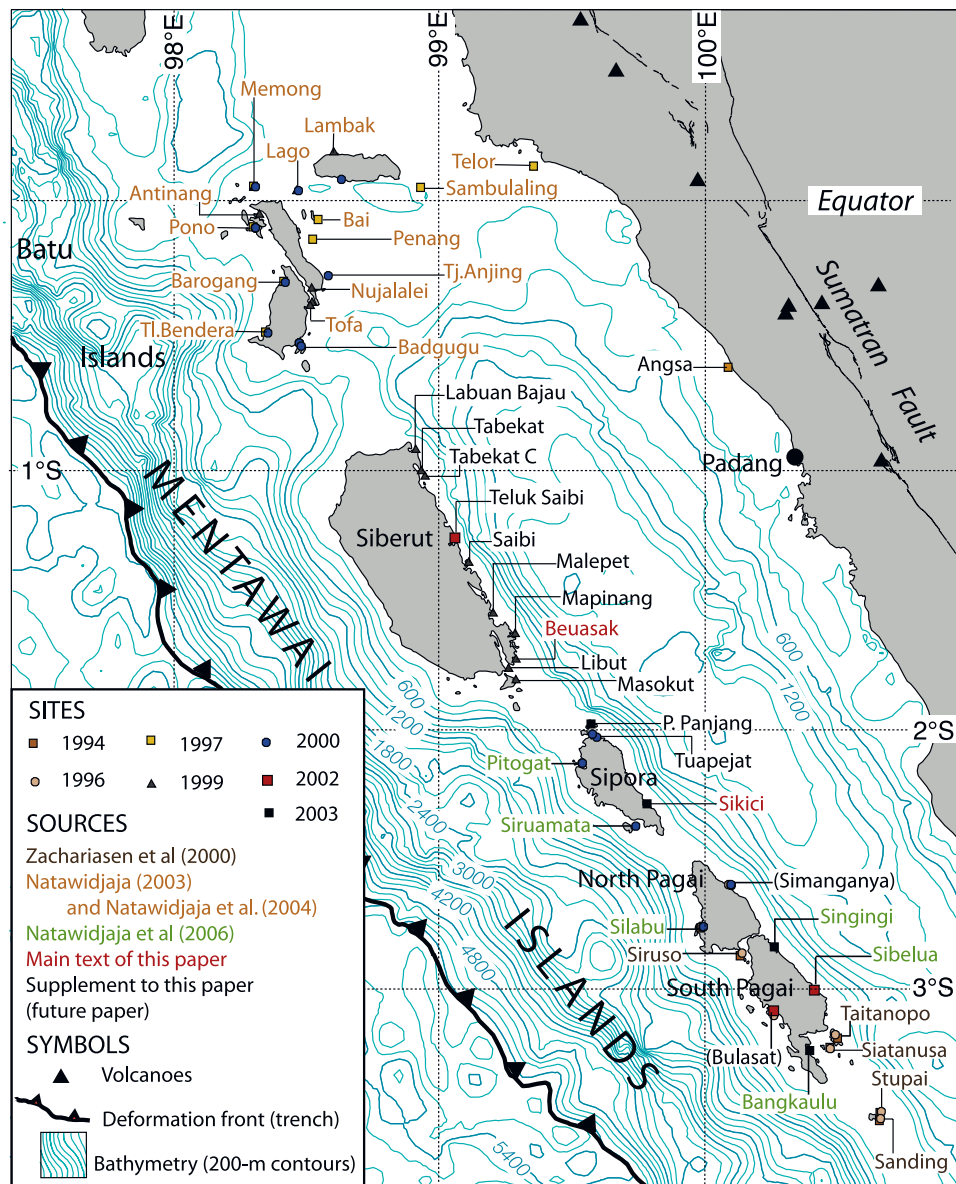
**Figure 2.** (continued)

wider than they are tall, and higher rates result in forms that are taller than they are wide. Microatolls on the southwestern coasts of the Mentawai islands are generally taller than they are wide, whereas those on the northeastern coasts are commonly wider than they are tall. Thus it is possible even prior to detailed analysis of microatoll stratigraphy to conclude that in general the islands are sinking faster along their southwestern coasts than they are along their northeastern coasts.

[12] The analyses of microatolls that appear below allow us to quantify rates and patterns of deformation. We

investigate the morphology and stratigraphy of microatolls from 28 sites. These comprise 10 sites along the east coast of Siberut island, 5 sites on Sipora island, 11 sites on and near the Pagai islands and neighboring islets and 2 near the mainland coast (Figure 3). These sites lie 95 to 250 km from the trench axis and span a 340-km length of the outer-arc islands.

[13] As a mercy to our readers, we describe in detail the evidence for vertical deformation at just two of the 28 sites. These two are representative, in that they span nearly the full range of microatoll morphologies and submergence



**Figure 3.** Map of the sampling sites discussed in this and previous papers. All but 2 of the 28 discussed in this paper are on the fringing reefs of the Mentawai islands. Two of these are described in this paper, and 12 are detailed in the auxiliary materials. Most of the others have already been documented in previous papers.

rates. After introducing the two sites in detail, we discuss each of the other sites briefly. We then use a compilation of the sea level histories to map geographical and temporal patterns of sea level change. Finally, we discuss the significance of these patterns.

## 2.2. Sikici

[14] This site is on Cape Sikici, a small salient on the east coast of Sipora island (Figure 3). The intertidal reef extends about 100 m seaward of the shoreline (Figure 4). Several generations of *Porites* and other genera of heads and microatolls sit within the intertidal zone along a kilometer-long arcuate stretch of the coast, centered on the cape. The cape is underlain by steeply southwest dipping sedimentary rock, best exposed near the shoreline in the

intertidal zone. Locally, a cemented, highly eroded mid-Holocene reef platform sits upon the bedrock.

[15] Ongoing submergence is evident along the coast, as coconut palm root balls and patches of peat sit directly on the cemented reef, seaward of the beach, in the intertidal zone (Figure 4). In places along the shore, the peat extends under the modern beach sand and gravel. This is evidence for transgression of the beach and intertidal zone over terrestrial or swamp vegetation.

[16] At least five generations of coral exist at the site. The youngest is a thriving population of large living microatolls growing near the outer edge of the intertidal reef. Some of the living microatolls are about 4 m in diameter and a meter or more high. Many have wide, double, raised outer rims.

**Table 1.** U-Th Analyses of Samples From Corals Used in This Study<sup>a</sup>

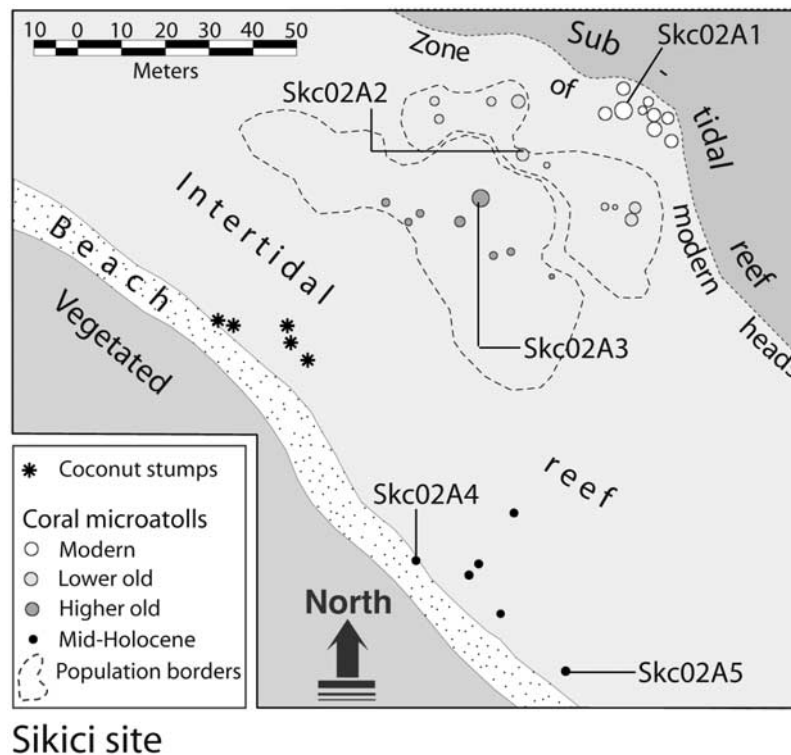
Sample	<sup>238</sup> U, ppb	<sup>232</sup> Th, ppt	<sup>230</sup> Th/ <sup>232</sup> Th, atomic × 10 <sup>-6</sup>	$\delta^{234}\text{U}^b$ Measured	<sup>230</sup> Th/ <sup>238</sup> U Activity	Year of Analysis, year A.D.	<sup>230</sup> Th Age, years		$\delta^{234}\text{U}_{\text{initial}}^c$ Corrected	Age, <sup>d</sup> years B.P.	Growth Year, years A.D.
							Uncorrected	Corrected			
Sk02A1-3b-I	2088 ± 2	2377 ± 6	17.1 ± 0.5	147.2 ± 1.2	0.00118 ± 0.00003	2003	112 ± 3	70 ± 40	147.2 ± 1.2	17 ± 40	1933 ± 40
Sk02A1-3b-II	2142 ± 2	1573 ± 6	25.0 ± 0.6	146.2 ± 1.3	0.00111 ± 0.00003	2003	106 ± 3	78 ± 28	146.3 ± 1.3	25 ± 28	1925 ± 28
Tb02C1	2500 ± 3	3046 ± 7	12.9 ± 0.3	146.9 ± 1.4	0.00095 ± 0.00002	2003	91 ± 2	45 ± 46	146.9 ± 1.4	-8 ± 46	1958 ± 46
Tsa02B1-2b	2210 ± 2	827 ± 5	31 ± 1	147.4 ± 1.4	0.00070 ± 0.00003	2004	67 ± 2	53 ± 14	147.5 ± 1.4	-1 ± 14	1951 ± 14
Tsa02B1-4a	2587 ± 4	745 ± 5	57 ± 2	144.6 ± 2.2	0.00099 ± 0.00002	2004	94 ± 2	84 ± 11	144.6 ± 2.2	30 ± 11	1920 ± 11
Bs99A1-2	2601 ± 3	453 ± 16	11.4 ± 2.6	146.2 ± 1.0	0.00012 ± 0.00003	1999	11 ± 3	5 ± 7	146.2 ± 1.0	-44 ± 7	1994 ± 7
Bs99A1-3	2565 ± 3	667 ± 10	22.5 ± 0.9	145.5 ± 1.5	0.00035 ± 0.00001	1999	34 ± 1	24 ± 10	145.6 ± 1.5	-25 ± 10	1975 ± 10
Bs99A1-6	2684 ± 3	9244 ± 38	5.9 ± 0.2	147.1 ± 1.0	0.00123 ± 0.00004	1999	117 ± 4	-12 ± 129	147.1 ± 1.0	-61 ± 129	2011 ± 129
Bs99A1-7	2578 ± 3	589 ± 20	44 ± 3	147.4 ± 1.1	0.00061 ± 0.00004	1999	58 ± 4	49 ± 9	147.4 ± 1.1	0 ± 9	1950 ± 9
Ms99A7-2-I	2458 ± 2	1224 ± 13	8.5 ± 0.5	146.9 ± 0.9	0.00026 ± 0.00002	1999	24 ± 1	6 ± 19	146.9 ± 0.9	-43 ± 19	1993 ± 13
Ms99A7-2-II	2699 ± 3	2493 ± 34	4.7 ± 0.5	145.1 ± 1.2	0.00026 ± 0.00003	1999	25 ± 2	-10 ± 35	145.1 ± 1.2	-59 ± 35	2009 ± 35
Sb99D2-2	2560 ± 3	4623 ± 22	5.3 ± 0.8	146.0 ± 1.4	0.00058 ± 0.00008	1999	55 ± 8	-12 ± 68	146.0 ± 1.4	-61 ± 68	2011 ± 68
Sb99D2-4	2462 ± 3	3783 ± 21	7.6 ± 0.3	146.7 ± 1.2	0.00071 ± 0.00003	1999	68 ± 2	10 ± 58	146.7 ± 1.2	-39 ± 58	1989 ± 58
Lb99A1-1	2617 ± 3	14689 ± 98	6.5 ± 0.2	145.6 ± 1.1	0.00221 ± 0.00005	1999	211 ± 5	0 ± 211	145.6 ± 1.1	-49 ± 211	1999 ± 211
Lb99A3-4-I	2161 ± 2	1086 ± 20	26.2 ± 1.1	149.1 ± 1.0	0.00080 ± 0.00003	1999	76 ± 3	57 ± 19	149.1 ± 1.0	8 ± 19	1942 ± 19
Lb99A3-4-II	2221 ± 2	1507 ± 13	21.2 ± 0.9	149.2 ± 0.8	0.00087 ± 0.00004	1999	83 ± 4	58 ± 26	149.2 ± 0.8	9 ± 26	1941 ± 26
Sa99A1-5	2617 ± 3	1768 ± 22	13.2 ± 0.7	145.3 ± 1.2	0.00054 ± 0.00003	1999	52 ± 3	26 ± 26	145.4 ± 1.2	-23 ± 26	1973 ± 26
Mp99A1-2	2604 ± 3	3276 ± 37	53.8 ± 1.3	146.2 ± 1.0	0.00410 ± 0.00009	1999	392 ± 9	344 ± 48	146.3 ± 1.0	295 ± 48	1655 ± 48
Sb99B1-1	2382 ± 3	2756 ± 21	8.0 ± 0.3	146.9 ± 1.2	0.00056 ± 0.00002	1999	53 ± 2	10 ± 43	146.9 ± 1.2	-39 ± 43	1989 ± 43
Sb99B1-3-I	2161 ± 3	1492 ± 20	14.9 ± 0.7	146.5 ± 1.2	0.00062 ± 0.00003	1999	42 ± 9	33 ± 26	146.5 ± 1.2	-16 ± 26	1966 ± 26
Sb99B1-3-II	2165 ± 2	1293 ± 9	16.4 ± 0.4	146.8 ± 1.1	0.00059 ± 0.00002	1999	56 ± 1	34 ± 22	146.8 ± 1.1	-15 ± 22	1965 ± 22
Ll99A1-2-I	2484 ± 3	3058 ± 29	4.7 ± 1.3	146.5 ± 1.2	0.00035 ± 0.00009	1999	34 ± 9	-13 ± 47	146.5 ± 1.2	-62 ± 47	2012 ± 47
Ll99A1-2-II	2511 ± 2	2793 ± 28	7.7 ± 0.4	148.4 ± 0.9	0.00052 ± 0.00003	1999	50 ± 2	8 ± 42	148.5 ± 0.9	-41 ± 42	1991 ± 42
Ll99A1-9	3079 ± 4	19950 ± 150	4.2 ± 0.1	145.6 ± 1.1	0.00164 ± 0.00004	1999	157 ± 4	-87 ± 243	145.6 ± 1.1	-136 ± 243	2086 ± 243
Ll99A1-10	2604 ± 3	44320 ± 500	3.0 ± 0.1	145.6 ± 1.1	0.00314 ± 0.00008	1999	300 ± 8	-341 ± 640	145.5 ± 1.1	-390 ± 640	2340 ± 640

<sup>a</sup>All errors are reported at the 2σ level of uncertainty. Corrected <sup>230</sup>Th ages assume initial <sup>230</sup>Th/<sup>232</sup>Th atomic ratios of  $(6.5 \pm 6.5) \times 10^{-6}$ . The decay constant values used in calculating the ages are  $\lambda_{230} = 9.1577 \times 10^{-6} \text{ yr}^{-1}$ ,  $\lambda_{234} = 2.8263 \times 10^{-6} \text{ yr}^{-1}$ , and  $\lambda_{238} = 1.55125 \times 10^{-10} \text{ yr}^{-1}$ .

<sup>b</sup>The parameter  $\delta^{234}\text{U} = ((^{234}\text{U}/^{238}\text{U})_{\text{activity}} - 1) \times 1000$ .

<sup>c</sup>The parameter  $\delta^{234}\text{U}_{\text{initial}}$  was calculated based on <sup>230</sup>Th age (T), i.e.,  $\delta^{234}\text{U}_{\text{initial}} = \delta^{234}\text{U}_{\text{measured}} \times e^{\lambda^{234} \times T}$ .

<sup>d</sup>B.P. stands for “before present” where the “present” is defined as the year 1950 A.D.



**Figure 4.** Map of the Sikici site, northeastern coast of Sipora island. Modern heads are concentrated along the outer edge of the shallow reef. Coconut stumps just seaward of the modern beach are evidence of recent subsidence. Two populations of fossil microatolls in the intertidal zone died when uplifted in the 16th century. The tops of these are about 20 and 50 cm higher than the tops of the living, modern microatolls. The tops of mid-Holocene microatolls, near the beach, are about 75 cm above the tops of the modern microatolls. Only the slab Skc02A1, from one of the modern microatolls is discussed in this paper.

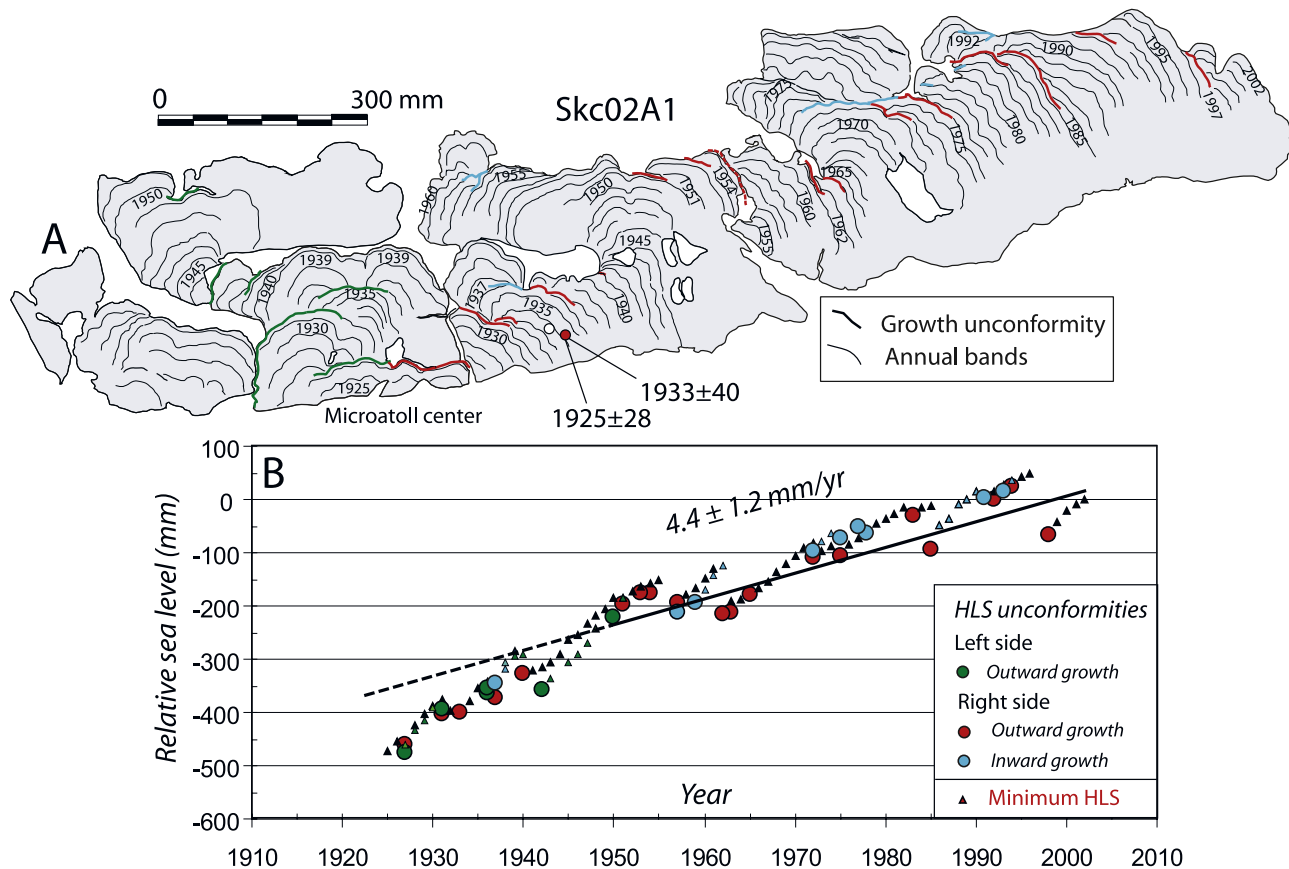
Sample Skc02A1 was cut from one of the largest of these living microatolls.

[17] The HLS history recorded in Skc02A1 extends through 74 years, from 1928 to 2002 (Figure 5). HLS unconformities occur in a large fraction of those 74 years, so sea level changes are particularly well constrained. From the history of HLS unconformities and their relative elevations, we can determine the history of submergence of the Sikici site. The procedure for doing this is laid out by Natawidjaja [2003] and Natawidjaja *et al.* [2004]. The site was submerging throughout the 74-year-long period, but rates of submergence within the period vary markedly from the average. Sea level during the 1940s appears to have been rising at a rate slightly greater than the rate at which the coral could grow upward, given the lack of HLS unconformities during that decade. That rate would have been about  $12 \text{ mm yr}^{-1}$ , judging from the difference in elevation of the 1940 and 1951 HLS unconformities. Another possibility is that an aseismic submergence event of about 130 mm occurred in about 1941, and upward growth occurred unhindered until the microatoll reached the new HLS in 1951. The microatoll records a period of nearly stable HLS through the 1950s and early 1960s. Between 1965 and 1971, HLS rose about 70 mm without any unconformities. Averaged over the past five decades, HLS has been rising at Sikici at about  $4.4 \text{ mm yr}^{-1}$ .

### 2.3. Beuasak

[18] The Beuasak site is an intertidal reef on a small islet just a few hundred meters off the southeast coast of Siberut Island (Figure 3). It is representative of rapidly subsiding sites. A family of modern *Porites* heads populates the outer part of the shallow intertidal reef (Figure 6). The few heads we measured rise 60 to 150 cm above the substrate, and their diameters range from 2 to 6 m. Many of the flat-topped, upright microatolls have a columnar growth pattern that is common at sites with submergence rates greater than about  $7 \text{ mm yr}^{-1}$ . Looking down at the flat upper surface of a microatoll, one sees dozens of closely packed but separate 10- to 20-cm-diameter columns, all growing upward at about the same rate. This growth habit is particular to microatolls that are striving to keep up with rapidly rising sea level. We surmise that when heads are submerging at rates just a little less than the maximum rate of possible upward growth, many coral polyps are able to recolonize the dead flat top of the microatoll. These compete effectively with each other for space and hence are each hemmed in by their neighbors. This leads to a population of columnar forms across the top of the microatoll. Among the sites near Siberut, Beuasak was unusual in that during our visit in mid-1999 we found three large *Porites* heads that had not succumbed to the regional 1997 reef disaster. The hemispherical upper surfaces of these heads were several centimeters below the tops of nearby microatolls, a clear





**Figure 5.** (a) Cross section of the Sikici microatoll and (b) graph of its HLS history. The slab includes an outer raised rim and an interior, lower flat. The record spans 7 decades of the 20th century and reveals episodic submergence at an average rate of about  $4 \text{ mm yr}^{-1}$ .

indication that they had not yet reached HLS. We saw no other living heads in mid-1999 along the coast of Siberut island.

[19] The Bs99A1 slab (Figure 7) came from a well-preserved dead modern microatoll that has a diameter of about 5 m. The 1-m-long slab we collected represents only the most recent five decades of HLS history contained in the head. The Beuasak slab has three basic components: A flat-topped and bulky older mass, a delicate flat-topped outer raised rim, and an intervening narrow arm. Most of the upward growth of the microatoll occurred during the formation of this narrow arm, between about 1962 and 1985. HLS was nearly stable during the 1940s, 1950s, 1980s, and 1990s.

[20] HLS during the period from about 1985 to 1997 is particularly well constrained, because erosion is minimal and the outer raised rim records this period on both its inner and outer perimeters (open and solid symbols in Figure 7b). It is quite clear that HLS was stable during this 12-year period. A least squares fit to the HLS unconformities yields a submergence rate of just a  $\text{mm yr}^{-1}$  or so.

[21] The oldest part of the slab also appears to record a period of HLS stability. The top of the rings that grew from 1946 to 1949 must represent HLS unconformities, because there would have been only a few years for any erosion to occur before overgrowth of the 1950 through 1954 bands.

Thus it seems likely that the latter half of the 1940s was a period of HLS stability at Beuasak.

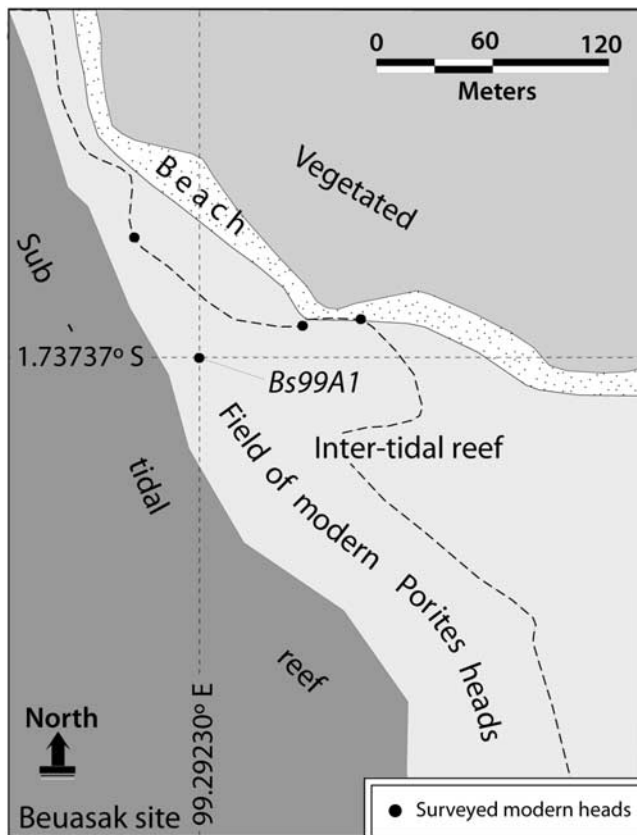
[22] Unfettered upward growth occurred from 1950 to 1953, and the next HLS unconformity occurred in 1954. The record is obscure, but HLS unconformities in 1955 and 1956 appear to have been at about the same level as in 1954. Thus a short period of stability may have occurred during the mid-1950s. Free upward growth occurred during the next 5 years.

[23] In 1962 a die-down of at least 80 mm occurred. This event demarcates a boundary between the preceding 16 years of slow average submergence rates and a subsequent two decades of upward growth at an average rate of more than  $10 \text{ mm yr}^{-1}$ . Between 1962 and 1985 upward growth is clipped unequivocally only twice, in 1968 and 1975. These two unconformities show that rapid submergence after 1962 occurred over an interval of at least 13 and perhaps as long as 23 years.

[24] The average rate of submergence of the Beuasak site between 1946 and 1997 is very rapid,  $7.4 \pm 0.3 \text{ mm yr}^{-1}$ . This is higher than the rates at most sites farther north along the coast of Siberut island. Even so, this high rate includes at least one and probably two decade-long periods of HLS stability.

[25] The high degree of preservation of the Beuasak record allows us to assess its HLS history in some detail. It is clear that the site has not experienced uniform subsi-





**Figure 6.** Map of the Beuasak site, northeastern coast of southern Siberut island. Modern heads grew in a band along the outer part of the shallow reef. We sampled microatoll Bs99A1.

dence throughout the past 50 years. The 12-year interval from 1985 through 1997 is clearly one of near stability. Likewise, the periods 1946–1950 and 1954–1956 are stable.

[26] Zachariasen [1998] and Zachariasen *et al.* [2000] tested whether or not a combination of rapid, uniform submergence and infrequent lowest low tides could actually produce a record of occasional HLS unconformities interspersed with periods of free upward growth. They found that long periods of unhindered upward growth and intervening clusters of HLS unconformities are unlikely to occur in this situation. The most likely manifestation of submergence rates nearly equal to the rate of unhindered upward growth is the interruption of long periods of unfettered upward growth by occasional, solitary HLS unconformities. Thus it seems most likely that the Beuasak site records three periods of decidedly different behavior. During the first period, from 1946 (or earlier) to 1962, short periods of HLS stability were interrupted by small submergence events or periods of rapid submergence. During the second period, from 1962 to 1985, rapid submergence at  $>10 \text{ mm yr}^{-1}$  prevailed. The microatoll record cannot discriminate whether that period was characterized by steady rapid submergence or by episodic rapid submergence. During the third period, from 1985 to 1997, HLS was nearly stable.

## 2.4. Other Sites

[27] In addition to the two sites that we have documented in detail, above, 26 other sites are relevant to understanding modern deformation along the Mentawai section of the Sunda megathrust. Documentation of 12 of these appears in auxiliary material to this paper.<sup>1</sup> We summarize the results from modern microatolls at the remaining 14 sites below. Twelve of these have been documented in detail in previous papers [Zachariasen *et al.*, 2000; Natawidjaja *et al.*, 2006] and the other two (Bulasat and Simanganya) will appear in a forthcoming paper (Figure 3). For convenience of reference, the HLS histories of all 28 sites appear in geographic order, from north to south, in Figure 8.

### 2.4.1. Pitogat

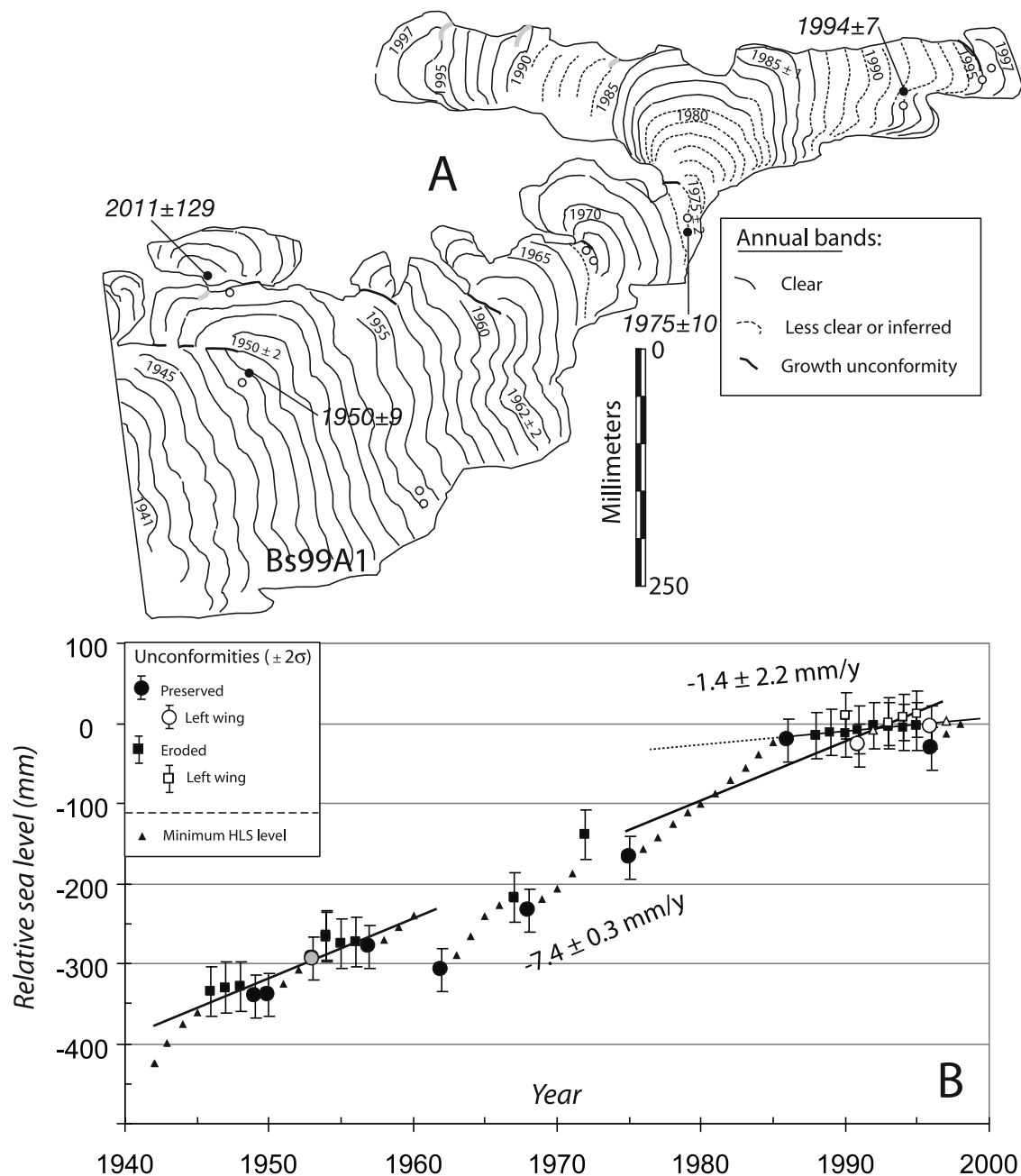
[28] Natawidjaja *et al.* [2006] describe the Pitogat site, on the west coast of Sipora island (Figure 3). Microatolls from both modern and fossil populations have raised outer rims. Slab Ptg00A1 came from the raised outer rim of one of the living modern heads. The HLS history of the slab spans the last four decades of the 20th century (Figure 8n). The outer raised rim began to grow in 1962. HLS history before that is obscure but the 1950s may have been or may have followed a time of rapid submergence. The average rate of submergence since the 1960s is about  $3.5 \text{ mm yr}^{-1}$ . Several clear HLS unconformities occur during that interval. One could argue that HLS rise was episodic, with short intervals of stability between HLS unconformities in 1962, 1964, 1972, 1978, and 1984. Nevertheless, the fact that the HLS unconformities are solitary suggests that HLS rise was steady. During the interval from 1988 to 2000, the trend reverses and emergence occurs at an average rate of about  $1.2 \text{ mm yr}^{-1}$ . Distinct HLS unconformities occur in 1990, 1994, and 1997. The reversal in trend began before the pronounced low tides of 1994 and 1997, with the unconformity in 1990, so a tectonic origin is plausible. This is the only one of our Mentawai sites that shows a pronounced reversal in HLS trend beginning before the exceptionally low tide of 1994 and the regional reef death of 1997.

### 2.4.2. Siruamata

[29] Siruamata is an islet about 500 m off the southwestern coast of Sipora island (Figure 3). Sample Srm00A1 is a slab from one of many large living *Porites* microatolls along the edge of a mangrove forest that covers most of the eastside of the islet [Natawidjaja *et al.*, 2006]. These modern heads sport the high height-to-width ratio and tall outer raised rim that are indicative of rapid submergence. The slab includes the outer raised rim and a substantial part of the older interior.

[30] The stratigraphy and morphology of slab Srm00A1 shows that, as at Pitogat, the outer raised rim began to form in about 1962 (Figure 8p). HLS appears to have been nearly stable in the several years prior to that. Since 1962, upward growth of the coral has barely been keeping pace with rising HLS; significant HLS unconformities appear in 1970s and early 1980s, 1994 and in 1997, but most of the annual bands display free upward growth. The average late 20th century submergence rate at this site is about  $8.3 \text{ mm yr}^{-1}$ .

<sup>1</sup>Auxiliary materials are available in the HTML. doi:10.1029/2006JB004450.



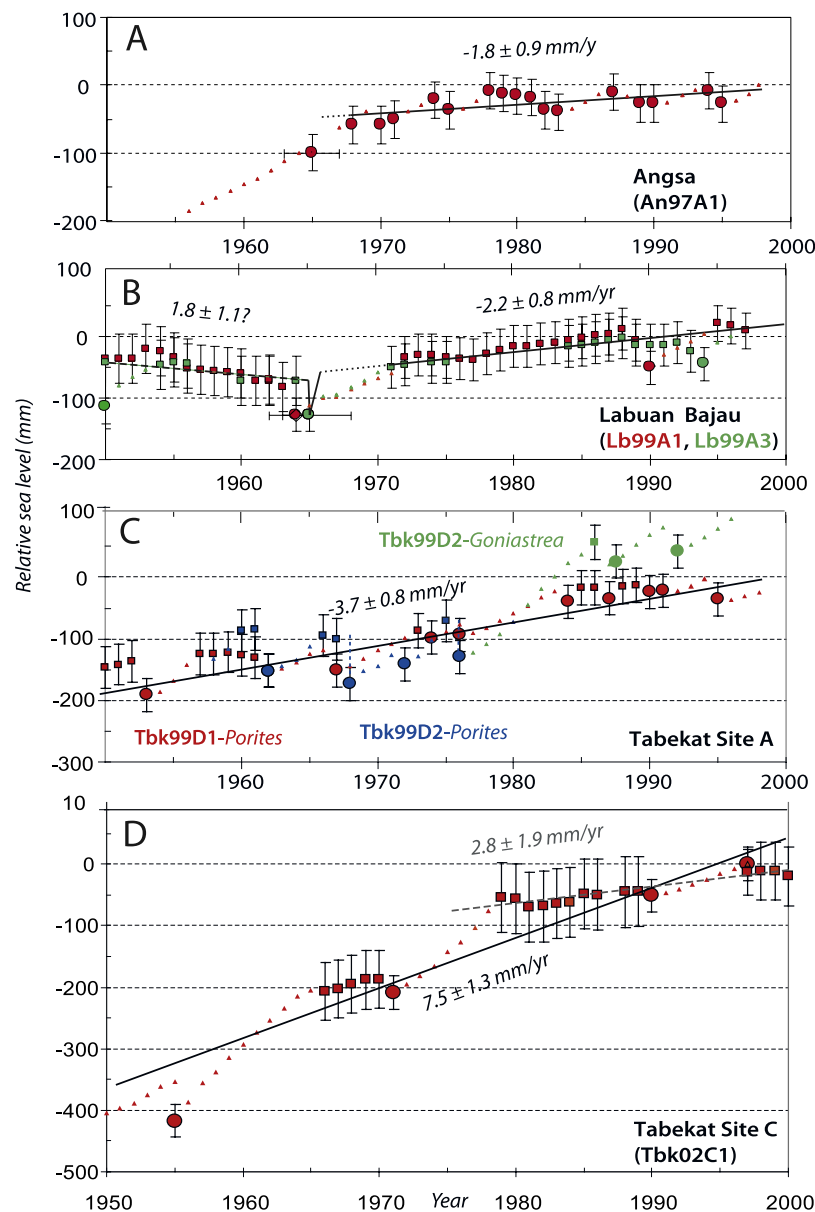
**Figure 7.** (a) Cross section of the modern Beuasak slab and (b) graph of its HLS history. The low interior flat and high flat of the outer raised rim formed during periods of relative HLS stability. The thin arm that separates them grew during the period 1962–1985, when HLS unconformities were uncommon. The long-term average rate of submergence is about  $7.4 \text{ mm yr}^{-1}$ , but the rate has been much slower since about 1985.

### 2.4.3. Simanganya

[31] The Simanganya site is on the northeast coast of North Pagai island (Figure 3). The site contains an abundance of large living microatolls and several generations of fossil heads as well. A detailed description of the site will appear in a paper on the repetition of large ruptures beneath the Mentawai islands. The modern heads are concentrated in a belt near the outer edge of the intertidal reef and have diameters as large as 3 m. The cup-shaped morphology of the living microatolls testifies to the predominance of submergence throughout the past several decades. Those

microatolls that survived the devastation of 1997/1998 have living perimeters about 50 to 150 mm lower than the crests of the pre-1997 bands. The slab we cut in mid-2000, Np00A1, is typical in this regard (Figure 8q).

[32] As with heads at Pitogat and Siruamata, the outer raised rim of Np00A1 began to form in about 1962, following an 80-mm die-down in that year. Several subsequent small die-downs in 1968, 1973, 1975, 1982, 1983, 1987, 1992, 1994, and 1995 impeded upward growth. The fact that some of these unconformities are clustered (in the mid-1970s, mid-1980s and early 1990s) suggests that sub-



**Figure 8.** Summaries of HLS histories for all 28 microatoll sites. Ordering is from (a) north to (bb) south and axes are the same in all plots. These graphs facilitate comparison of rates and correlation of events. Error bars indicate  $1\sigma$  uncertainties. For each site, 50-year average rates are derived by regressing a line by the method of least squares to all data, except for the HLS produced by the anthropogenic die-down of 1997. Six graphs also contain rates of vertical deformation for the past few years recorded by continuous GPS (cGPS) stations nearby.

mergence may have been episodic, with periods of intervening stability. The average rate of subsidence has been about  $8 \text{ mm yr}^{-1}$ .

#### 2.4.4. Silabu

[33] The Silabu site is within a bay on the west coast of North Pagai island (Figure 3). The site has an abundance of both living and fossil *Porites* microatolls and has been described in detail by Natawidjaja *et al.* [2006]. Living heads occupy a narrow belt on the outer edge of the intertidal reef flat. These microatolls typically have a simple cup-shaped morphology indicative of recent submergence. Sample Slb00A1 is a slab from one of these heads. It includes an outer raised rim that began to form in about

1987 and the younger, outer part of a lower inner core that grew between the mid-1960s and 1987.

[34] The first HLS unconformity in the slab occurred in about 1983, on the top of the inner flat (Figure 8r). Although the rings that formed from 1983 through 1986 are slightly eroded, it is plausible that HLS was nearly stable during this period. The outer raised rim began to grow after this apparent period of stability. It grew upward without a single, clear HLS unconformity until 1999 at an average submergence rate of about  $9.7 \text{ mm yr}^{-1}$ . Contrasting scenarios for this submergence are (1) rapid, constant submergence at this rate and (2) sudden aseismic submergence of about 25 cm in the mid-1980s. The continuously

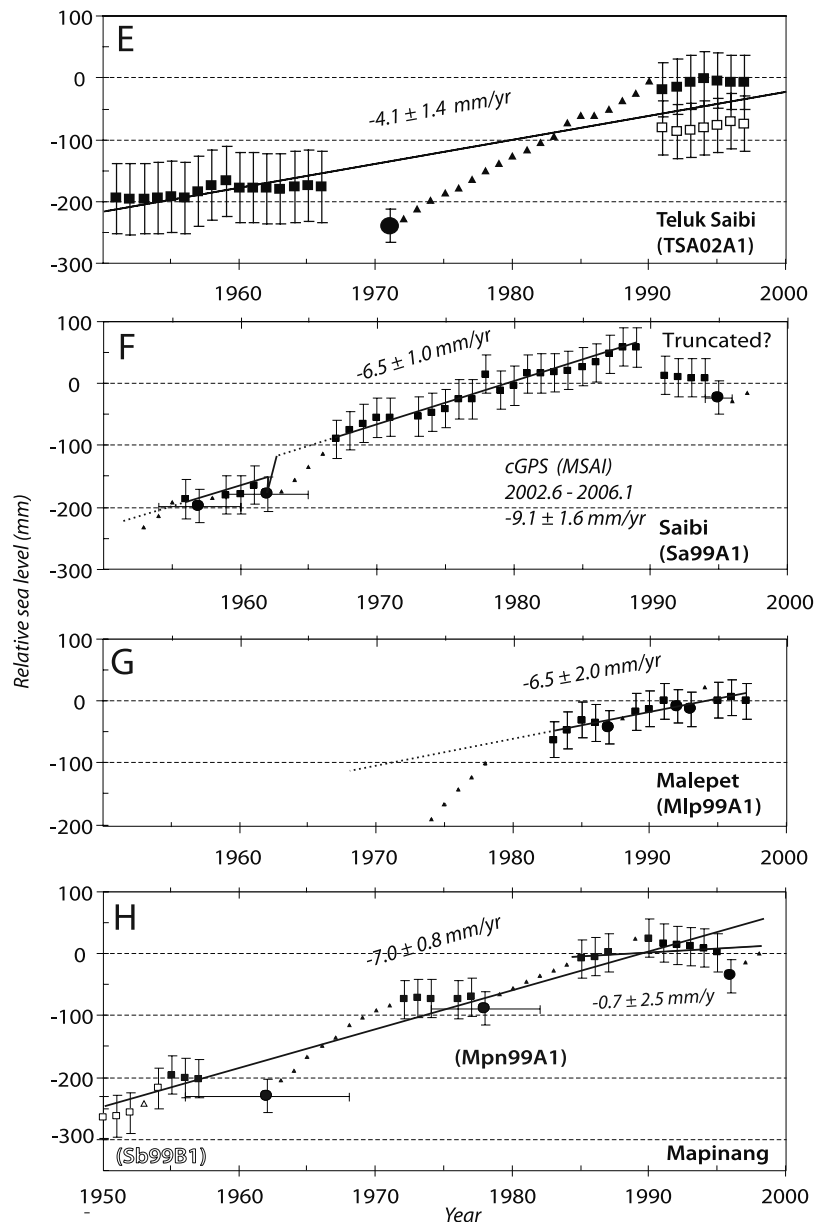


Figure 8. (continued)

recording GPS station, SLBU, about 2 km from the microatoll, yields an average rate of submergence of about  $15 \text{ mm yr}^{-1}$  between mid-2004 and early 2006 (<http://sopac.ucsd.edu/cgi-bin/dbShowArraySitesMap.cgi?array=SUGAR>). This very high rate of submergence over a 1.7-year interval suggests that neither scenario is correct. Instead, below average rates of submergence may be followed by above average rates.

#### 2.4.5. Singingi

[35] The Singingi site lies near the northeastern flank of South Pagai island, near the northern tip of the island (Figure 3). It is featured by Natawidjaja *et al.* [2006], because it has heads that date back to the giant 1797 and 1833 earthquakes. A slab from a modern head, Sgg03A3, reveals an HLS history that extends from about 1960 to 2003 (Figure 8s). As at many other sites, HLS appears to have been stable in the several years prior to 1962. Begin-

ning in 1962, a raised outer rim began to form. Free upward growth of about 240 mm continued until formation of an HLS unconformity in 1973. Since then, upward growth has been restricted by HLS to an average rate of about  $2.3 \text{ mm yr}^{-1}$ , with clear HLS unconformities in 1974, 1980, 1982, 1983, and 1997. The average rate of upward growth since the late 1950s has been about  $7.1 \text{ mm yr}^{-1}$ . This 50-year average rate is higher than that of the past 30 years because it includes the rapid, unrestricted upward growth of 1962 to 1973.

#### 2.4.6. Siruso Island

[36] Siruso island sits at the western entrance to Sikakap strait, the narrow corridor that separates North and South Pagai (Figure 3). Zachariasen *et al.* [2000] illustrate and describe a modern slab, P96B2, which they cut from a small microatoll there. The slab includes the outer raised rim and a fragment of the inner core of the head. The oldest bands of



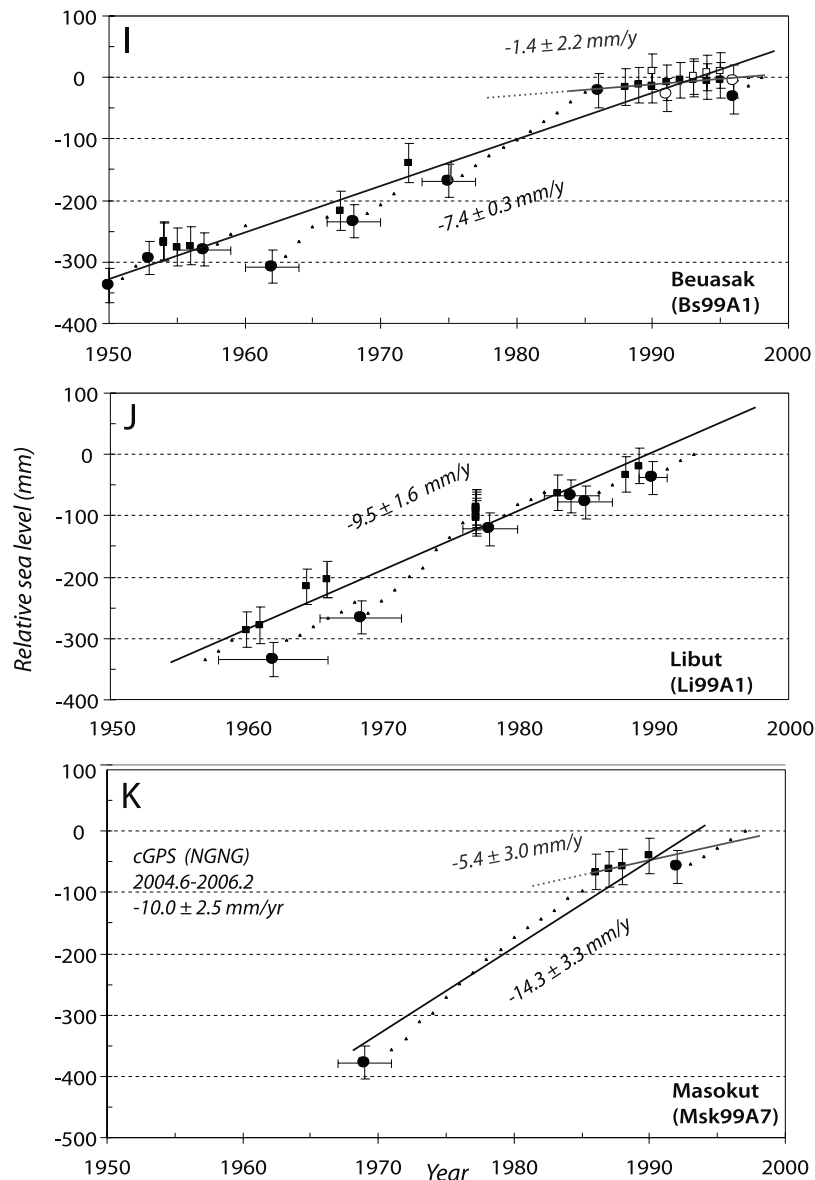


Figure 8. (continued)

the outer raised rim were not recovered, but the morphology of the oldest recovered bands hints that the date of inception of the raised rim antedates 1968 by no more than a few years. All of the bands from 1981 through 1984 are clipped at about the same elevation (Figure 8t).

[37] Other than this period of HLS near stability and a die-down in late 1995, all of the growth bands show uninhibited upward growth. Thus Siruso island appears to have experienced a short period of HLS stability (1981 to 1985) and two episodes of very rapid average submergence (pre-1968 to 1981 and 1985 to 1995). These two periods could, alternatively, have been preceded by sudden, large emergences of >160 and about 100 mm, respectively. A least squares fit to all HLS unconformities yields an average submergence rate of  $8.8 \pm 2.1 \text{ mm yr}^{-1}$  (Figure 8t).

#### 2.4.7. Sibelua

[38] The Sibelua site lies on the northeastern coast of South Pagai island (Figure 3). It is described in detail by Natawidjaja *et al.* [2006] because it contains a clear record

of the 1797 and 1833 ruptures. The modern microatoll slab from the site, Sbl02A2, shows two episodes of rapid growth of an outer raised rim, 1958 to about 1970 and 1986 to 1995 (Figure 8u). HLS unconformities are common in the intervening 15 years. The record is too truncated to tell whether or not HLS was stable in the mid-1950s, prior to inception of growth of the outer raised rim. The 40-year average rate of submergence is about  $6.0 \text{ mm yr}^{-1}$ , but submergence is clearly episodic. The nearby cGPS station of PRKB shows a comparable average rate of subsidence,  $10.2 \text{ mm yr}^{-1}$ , between the time of its installation in mid-2004 and early 2006.

#### 2.4.8. Bulasat

[39] Bulasat is a village on the central southwest coast of South Pagai (Figure 3). On the northern edge of the broad, arcuate bay in front of the village is a reef that contains several populations of fossil microatolls. The modern microatoll that we slabbled at the Bulasat site is a cup-shaped head with a broad and high outer raised rim. As

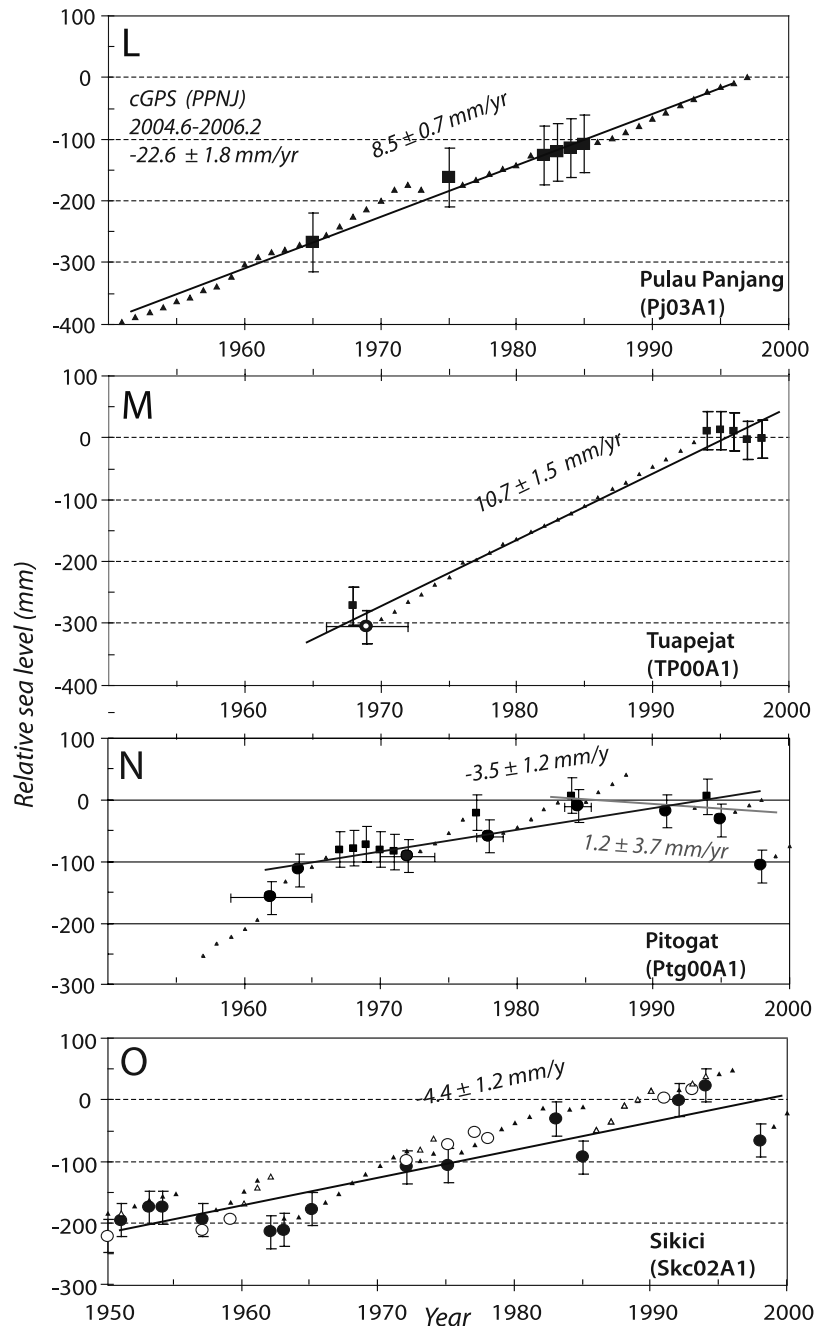


Figure 8. (continued)

elsewhere, the outer raised rim rises from a central core that experienced a 90-mm die-down in about 1960 (Figure 8v). Free upward growth of about 350 mm continued throughout the period about 1960–1979. In about 1979 a 120-mm die-down occurred. Following this, the outer rim grew upward an additional 150 mm until 1992. Progressively larger HLS unconformities in 1992, 1995, and 1998 have produced a net emergence of the head over the past decade at an average rate of about  $12 \text{ mm yr}^{-1}$ .

[40] The average rate of submergence of the head, between 1960 and 1990, is the highest we have measured at any site, about  $13.4 \text{ mm yr}^{-1}$ . A couple kilometers from

the modern microatoll is the continuously recording GPS site BSAT, which recorded an average rate of subsidence of about  $9 \text{ mm yr}^{-1}$  in the 3.5 years between late 2002 and early 2006 (<http://sopac.ucsd.edu/cgi-bin/sugarTimeSeries.cgi>). This high rate of subsidence indicates that the apparent high rate of emergence of the 1990s is no longer occurring.

#### 2.4.9. Tinopo Island

[41] Zachariasen *et al.* [2000] collected slab P96K2 from a microatoll on Tinopo islet in the archipelago of south-eastern South Pagai (Figure 3). Living microatolls at this

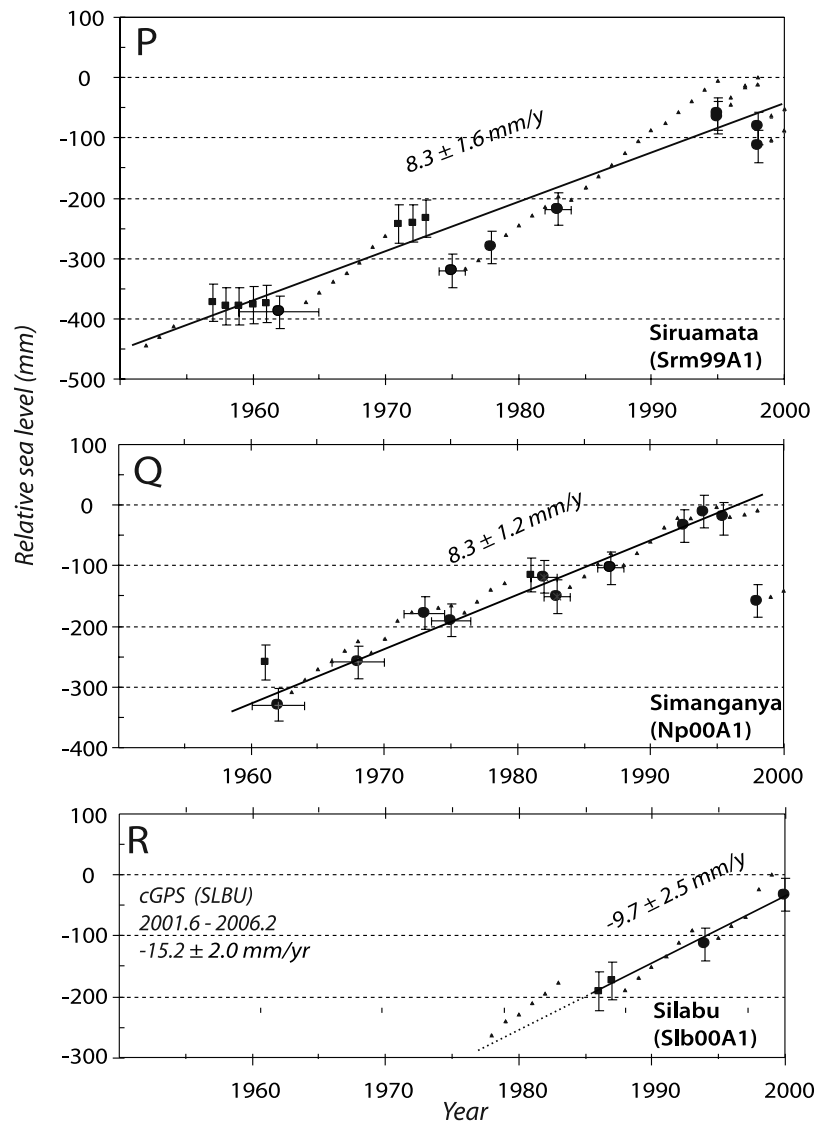


Figure 8. (continued)

site characteristically have low outer raised rims, which indicate that recent submergence rates have been low relative to the sites discussed above.

[42] None of the inner head was recovered from P96K2, but the shape of the oldest bands in the outer raised rim indicates that the rim began to form in about 1959. Most of the annual bands within the outer raised rim display free upward growth (Figure 8w). Consecutive HLS unconformities from 1969 to 1974 mark a period of stability, which ended with a 3-cm die-down in 1976. Another period of stability appears as several HLS unconformities between 1988 and 1996. From 1976 to 1988 the outer rim grew nearly unimpeded 100 mm upward.

[43] The average rate of submergence during the entire period is about  $4.1 \text{ mm yr}^{-1}$ , but this submergence occurred episodically. The average rate of submergence for the periods 1969–1975 and 1988–1996 is near zero.

#### 2.4.10. Siatanusa Island

[44] Siatanusa is another small islet off the southeastern coast of South Pagai (Figure 3). Like the slab from nearby

Tinopo, the slab that Zachariassen *et al.* [2000] recovered from this island (P96J3) consists of a broad, low raised rim. The slab shows that the rim began growing in about 1956, after a die-down of about 20 cm on the perimeter of the inner head. The microatoll experienced nearly unimpeded upward growth, interrupted by solitary HLS unconformities only in about 1981, 1983, and 1995 (Figure 8x). The least squares average submergence rate derived from the three HLS unconformities is about  $5.2 \text{ mm yr}^{-1}$ . All of the net submergence of about 320 mm was attained, however, during the period of unrestricted upward growth from 1956 to 1981.

#### 2.4.11. Bangkaulu

[45] The Bangkaulu site is on the east coast of the long narrow peninsula that extends southeastward from the main body of South Pagai (Figure 3). Natawidjaja *et al.* [2006] have described the site in detail. The slabbed modern microatoll from the site lives about 60 m offshore. It contains an excellent record of episodic rise of the HLS (Figure 8y). Clear annual banding in the slab leaves little

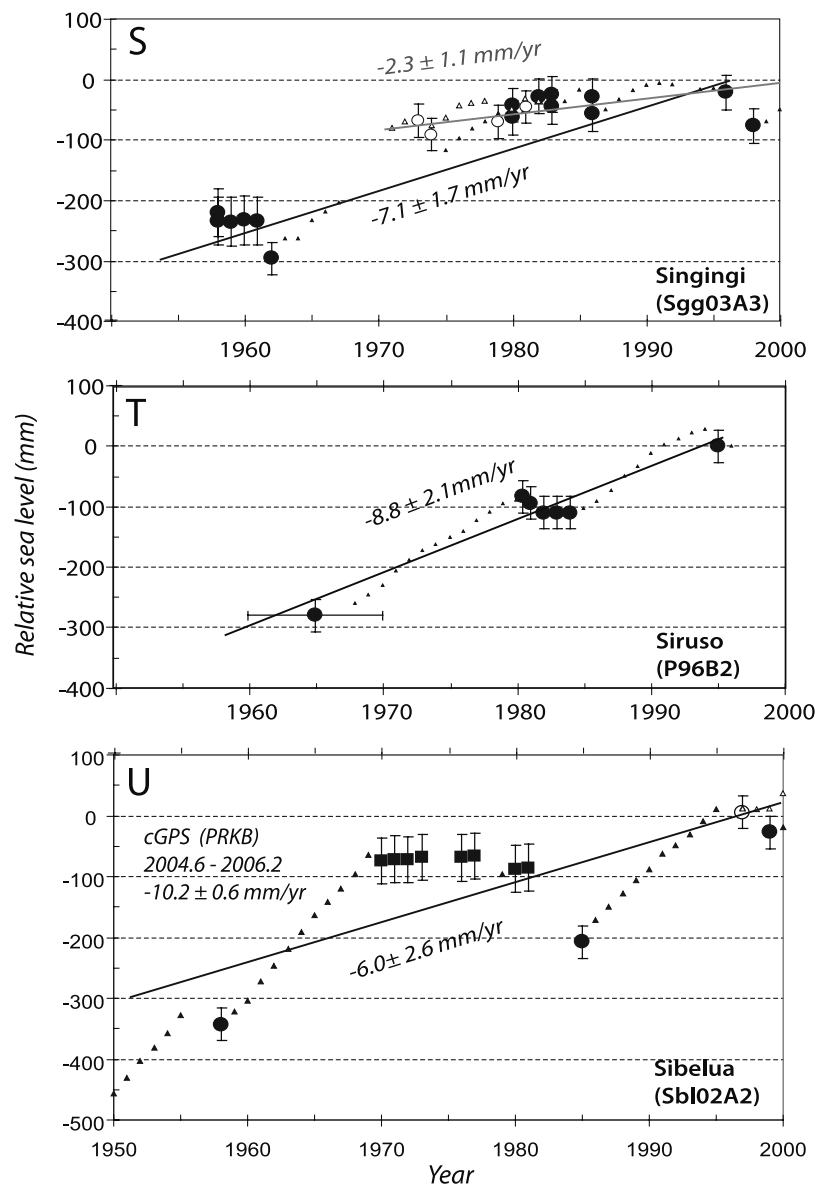


Figure 8. (continued)

uncertainty in the assignment of dates to the bands and three U-Th dates confirm this. The central core of the head suffered a clear die-down of a few centimeters in 1962. The outer raised rim began to grow immediately thereafter. Unimpeded upward growth of about 180 mm occurred between 1962 and 1975. HLS unconformities occurred in the mid-1970s and again in about 1980. These were followed by unimpeded growth of about 160 mm until 1991. Clear die-downs occurred during the El Niño years 1994 and 1997. The average rate of climb of the HLS between 1962 and 2002 is about  $7.1 \text{ mm yr}^{-1}$ .

#### 2.4.12. Stupai, Sanding, and Mega Islets

[46] Slabs Sd96A1 and Sd96C1 were collected by Zachariassen *et al.* [2000] from Stupai and Sanding, two islets on the outer-arc ridge about 30 km south of South Pagai. The two corals from which the slabs were cut are about a kilometer apart. The morphologies and HLS histories of these slabs differ only in their second-order features.

Both slabs are from the thick outer raised rim of a cup-shaped microatoll.

[47] The slab from Stupai (Sd96A1) exhibits a long period of nearly unfettered upward growth from the early 1950s until 1990, interrupted by small HLS unconformities only in the early 1980s (Figure 8z). The elevation of the 1996 HLS unconformity is nearly identical to that of the early 1980s. This suggests that the site was nearly stable throughout the 1980s and 1990s. A lack of HLS unconformities throughout the 1960s and 1970s suggests a history involving either a large, rapid submergence in the early 1950s or steady submergence throughout the period at a rate faster than the upward growth rate of the corallites. The average submergence rate for the entire period is about  $9.5 \text{ mm yr}^{-1}$ .

[48] The slab from Sanding islet (Sd96C1) comes from the thick raised perimeter of a living microatoll. Our best estimate of annual band dates, based on visual ring counting



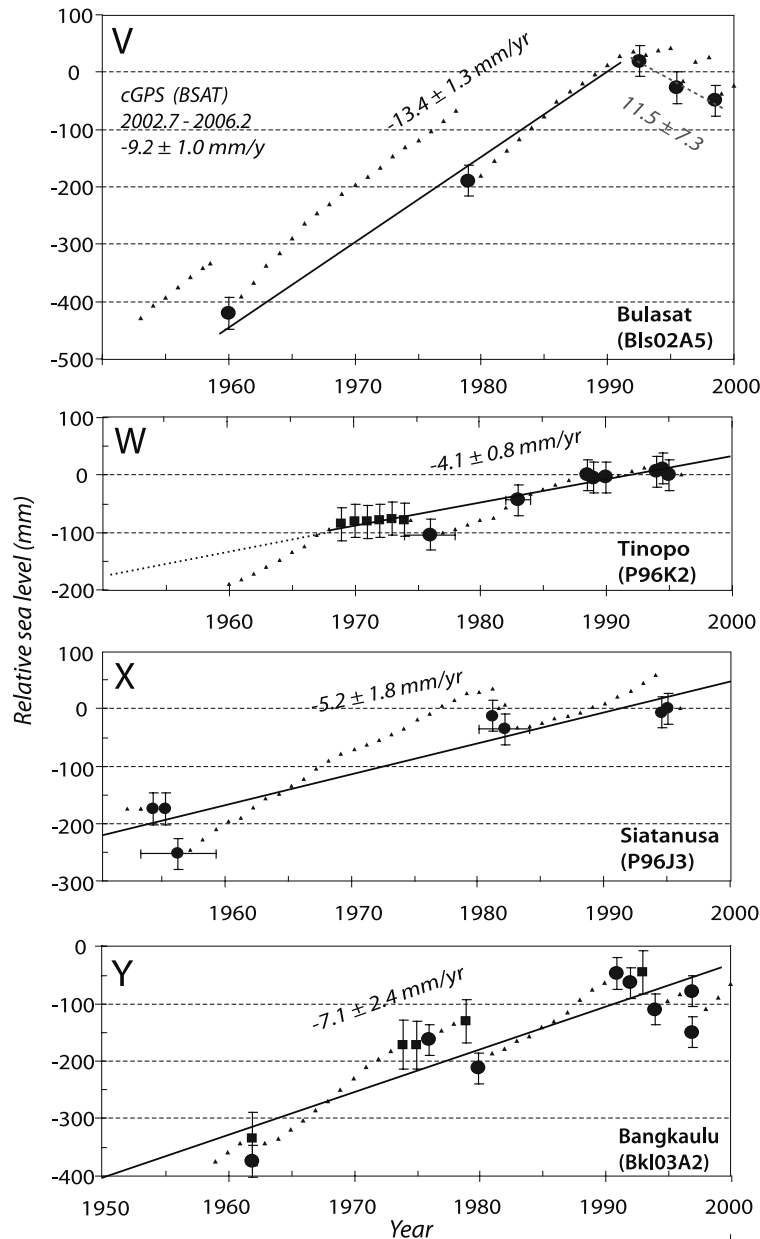


Figure 8. (continued)

of the slab differs from that of *Zachariasen et al.* [2000] by about 4 years in 30 counts. This difference is within their stated counting uncertainty. Annual banding is generally clear in the bands between 1980 and 1996 but is subdued in the bands that formed between 1980 and 1965 (Figure 8aa). Sd96C1 exhibits free upward growth except for a solitary HLS unconformity in the 1960s and two more in about 1987 and 1993. The average rate of subsidence between 1942 and 1995 is about  $10 \text{ mm yr}^{-1}$ .

[49] About 70 km southeast of Sanding island, at  $4.0^\circ\text{S}$ , is a miniscule islet, ironically named Mega (M in Figure 1). It is the only piece of the outer-arc ridge that rises above sea level between the islands Sanding ( $3.5^\circ\text{S}$ ) and Enganno ( $5.5^\circ\text{S}$ ). We have not collected samples from microatolls on Mega, but while scouting for possible GPS sites in August 2005 one of us (J. E. Galetzka) observed two living micro-

atolls in a lagoon there. Each head was about 1.5 m wide. Each sported an outer raised rim that was a fraction of a meter wide and rose about 0.3 m above a central flat. If we assume that the rims began to grow in about 1960, as we have seen at many other sites, then the rate of subsidence recorded by the heads must be close to the rates documented at Sanding and Stupai, that is, nearly  $10 \text{ mm yr}^{-1}$ .

#### 2.4.13. Tikos Island

[50] Tikos is an islet at about  $3.8^\circ\text{S}$ , just off the mainland coast near the city of Bengkulu (too far south to appear on Figure 3). *Zachariasen et al.* [2000] described the site and two modern microatolls there. The microatolls on Tikos island are flat-topped. The HLS history derived from the slab T96A1 spans the period 1980 to 1996, the year of collection. No annual band displays free upward growth. This is an indication that interannual HLS variations are no

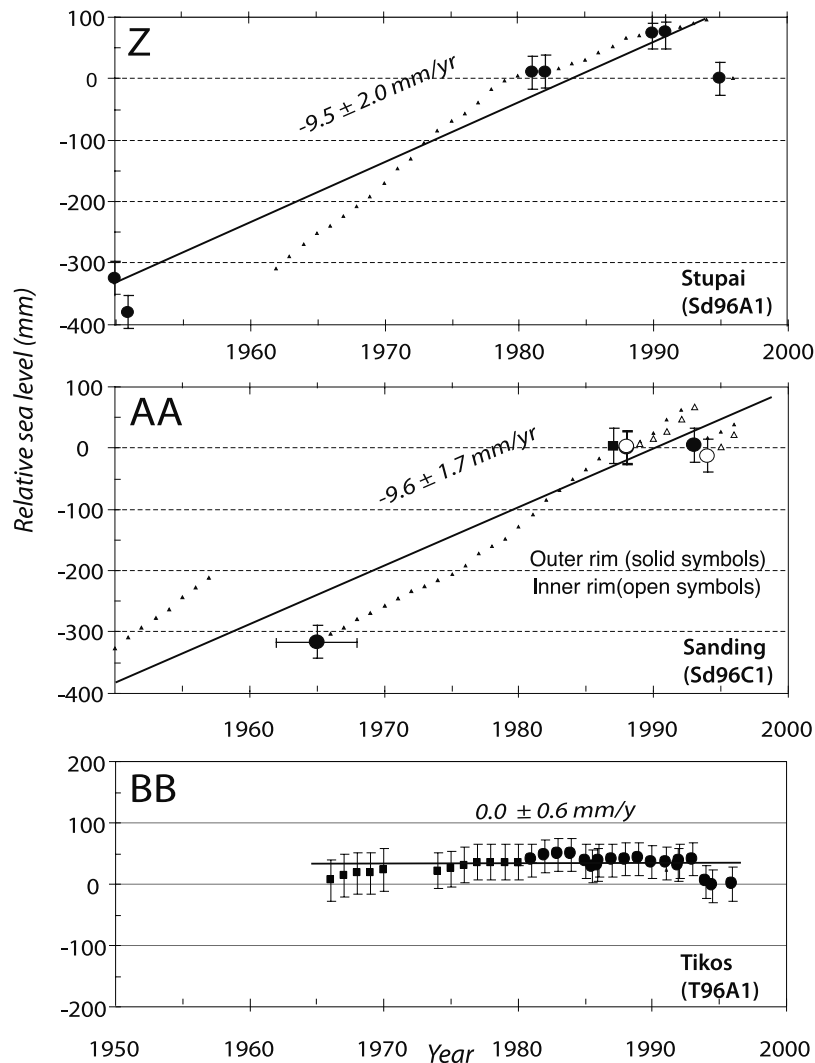


Figure 8. (continued)

greater than a few centimeters. A least squares fit to all HLS unconformities on the slab yields a rate of submergence of  $0.0 \pm 0.6$  mm yr<sup>-1</sup> (Figure 8bb).

### 3. Discussion and Interpretation

[51] From the evidence just presented, it is clear that the Mentawai islands have been subsiding during the past five decades. However, it is also clear that the subsidence has been uniform neither in space nor in time. The coral microatolls show that average rates of subsidence vary from site to site and vary commonly from decade to decade as well. In this section, we search for coherent geographic and temporal patterns in the data that might help elucidate the causes of the subsidence. Although clear temporal variations occur at many sites, we consider first the pattern of deformation averaged over the entire 50-year period, 1950–2000. Then we examine rates averaged over just the last two decades of the 20th century. Then we examine a particularly interesting episode of deformation in about 1962.

[52] Figure 8 and Table 2 are compilations of the data. In Figure 8, the 28 time series are ranked from north to south,

at the same scale and for the same period of time (1950–2000). Table 2 lists 20-year and 50-year average rates for all the sites and for 16 additional time series from Batu islands sites, the evidence for which is given by *Natawidjaja et al.* [2004]. Both averages are calculated by least squares regression on all the HLS unconformities for two periods, except the anthropogenic unconformity of 1997.

#### 3.1. Average Rates Over the Past Half Century

[53] Several general geographic trends are apparent in the 50-year averages (Figure 9). The first-order pattern is tilt away from the mainland; subsidence rates near the mainland coast are lower than those on the mainland (northeast) side of the islands, which generally are lower than those on the seaward (southwest) side of the islands. The low rates along the mainland coast are, in fact, approximately equal to the rate of global hydroisostatic rise in sea level over the past several decades [Church and White, 2006], so the tectonic component is about nil. Subsidence rates on the islands range from about 2 to about 14 mm yr<sup>-1</sup>. The faster rates are markedly higher than the fastest rates on the Batu islands, though at similar distances from the trench. Cross-strike tilt is constrained best across southern Sipora

**Table 2.** Subsidence Rates of Coral Microatolls in the Batu and Mentawai Islands and Mainland Sumatran Coast

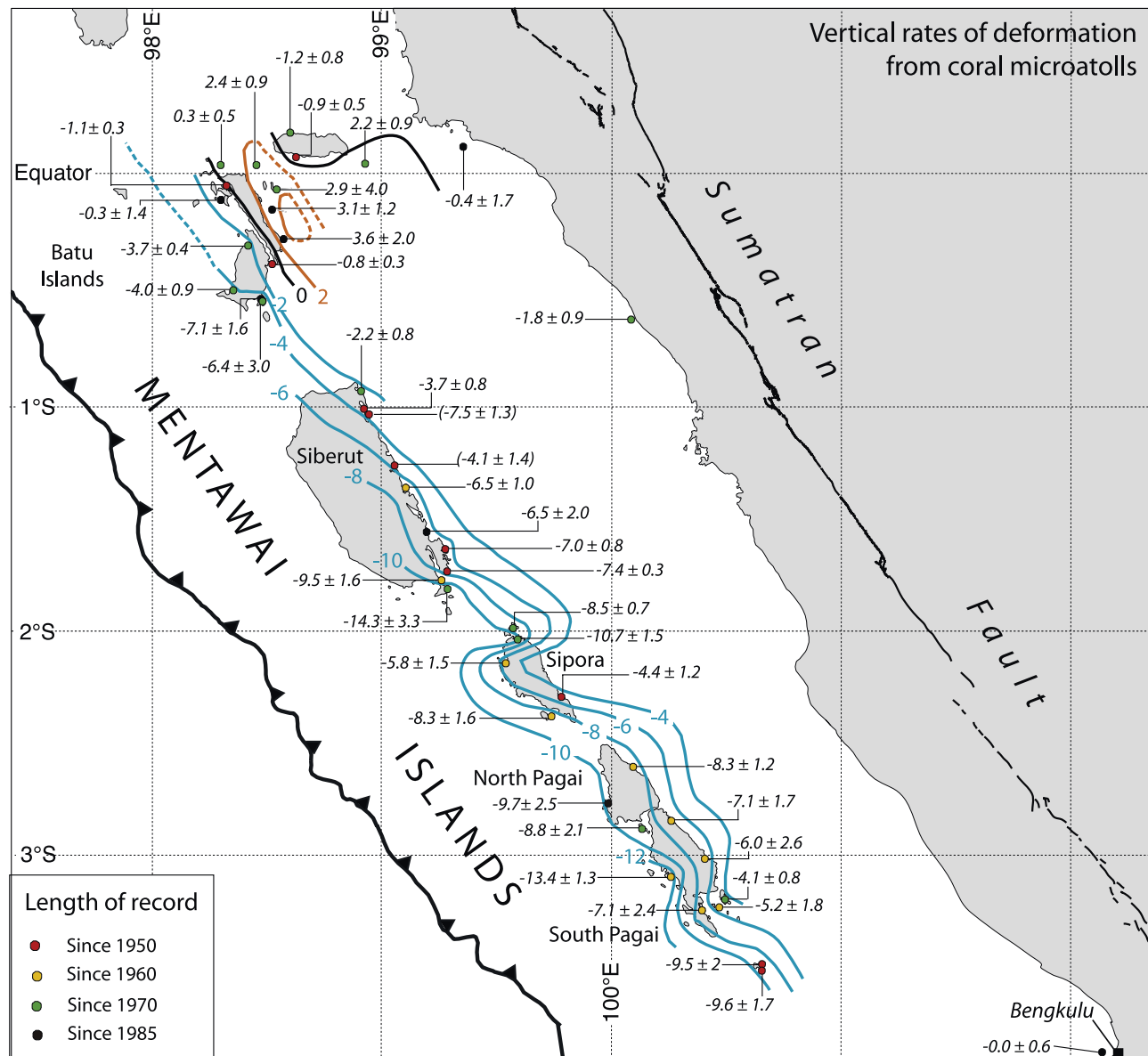
Location	Sample	Longitude	Latitude	50-year Rate			20-year Rate		
				Post-1950	1 $\sigma$	Data Span	Post-1980	1 $\sigma$	Data Span
Batu Islands									
Bendera	Tb00A1	98.34517	−0.50046	−4	0.9	1950–2000	−3.2	1.7	1970–2000
Badgugu-A	Bdg99A1	98.46383	−0.53921	−7.1	1.6	1952–1997	−6.7	2.3	1983–1997
Badgugu-B	Bdg00B1	98.47135	−0.54982	−6.4	3	1945–1998	−5.1	3.2	1975–1997
Barogang	Brg00A1	98.41148	−0.30814	−3.7	0.4	1950–1997	−2.4	0.6	1970–1997
Pono	Pn97&00A3	98.2973	−0.1021	−0.3	1.4	1970–1985	2.7	1.8	1986–1997
Antinang	At99A1	98.32066	−0.05011	−1.1	0.3	1950–1997	−1.1	0.3	1950–1997
Tofa	Tf99C1	98.5217	−0.38391	−0.8	0.3	1950–1997	−0.8	0.3	1950–1997
Memong	Mm97&99	98.2977	0.053	0.3	0.5	1966–1997	0.3	0.5	1966–1997
Tanjung Anjing	Taj00A1	98.5743	−0.28378	3.6	2	1985–1997	3.6	2	1985–1997
Penang	Pe97-1	98.523	−0.1486	3.1	1.2	1975–1997	4	1.9	1983–1997
Lago	Lg99A1	98.46046	0.03942	2.4	0.9	1969–1997	0.9	4.4	1969–1997
Bais	Ba97	98.5438	−0.0739	2.9	4	1958–1997	4.4	3.9	1972–1887
Masin	Msn00A1	98.62361	0.08225	−0.9	0.5	1950–1991	−0.9	0.5	1950–1991
Lambak	Lm99A1	98.60184	0.18609	1.2	0.8	1971–1996	1.2	0.8	1971–1996
Sambulaling	Sm97-1	98.9316	0.048	2.2	0.9	1970–1996	2.2	0.9	1970–1996
Telur	Te97-1	99.3597	0.1286	−0.4	1.7	1983–1997	−0.4	1.7	1983–1997
Siberut Island and Neighboring Mainland									
Labuan Bajau	Lb99A1&A3	98.91245	−0.94161	−2.2	0.8	1972–1997	−0.8	2	1985–1997
Tabekat A	Tbk99D1-2	98.94749	−1.04308	−3.7	0.8	1946–1995	0.1	2.9	1984–1998
Tabekat Site C	Tbk02C1	98.94708	−1.03969	−7.5	1.3	1955–2001	−2.8	1.9	1979–2002
Teluk Saibi	Tsa02A1	99.07342	−1.26871	−4.1	1.4	1951–1997			
Saibi	Sa99A1	99.11329	−1.37063	−6.5	1	1956–1989			
Malepet	Mlp99A1	99.20546	−1.56169	−6.5	2	1977–1997	−4.3	2.7	1983–1997
Mapinang	Mpn99B1&2	99.28944	−1.63937	−7	0.8	1951–1998	−0.7	2.5	1985–1998
Beusasak	Bs99A1	99.2923	−1.73737	−7.4	0.3	1946–1998	−1.4	2.2	1986–1999
Libut	Li99A1	99.26492	−1.77189	−9.5	1.6	1960–1997	−5.6	2	1970–1999
Masokut	Msk99A7	99.29427	−1.82509	−14.3	3.3	1969–1997	−5.4	3	1986–1997
Angsa	An97A1	100.0977	−0.6332	−1.8	0.9	1965–1997	−0.3	1.2	1978–1997
Sipora and Pagai Islands and Neighboring Mainland									
Pulau Panjang	Pjg03A1	99.59751	−1.99457	−8.5	0.7	1934–1985	−8.5	0.7	1934–1997
Tuapejit	Tp00A1	99.59202	−2.03311	−10.7	1.5	1968–1998			
Sikici	Skc02A1	99.80205	−2.28942	−4.4	1.2	1951–2002	−5.9	2.3	1972–2000
Pitogat	Ptg00A1	99.53567	−2.13171	−3.5	1.2	1962–1985	1.2	3.7	1984–2000
Siruamata	Srm00A1	99.7406	−2.37033	−8.3	1.6	1957–2000	−8.3	1.6	1957–2000
Silabu	Slb00A1	99.99514	−2.75205	−9.7	2.5	1986–2000	−9.7	2.5	1986–2000
Simanganya-A	Np00A1	100.1015	−2.59419	−8.3	1.2	1962–2000	−8.3	1.2	1962–2000
Singingi	Sgg03A3	100.28281	−2.82588	−7.1	1.7	1958–2003	−2.3	1.1	1973–2003
Bulasat	Bls02A5	100.3111	−3.12747	−13.4	1.3	1955–2002	11.5	7.3	1992–2002
Sibelua	Sbl02A2	100.46251	−3.03799	−6	2.6	1956–2002	−7.9	5.3	1980–2002
Bangkaulu	Bkl03A3	100.44658	−3.28521	−7.1	2.4	1962–2003	−4.5	3.1	1974–2003
Siruso	P96B2	100.15215	−2.85263	−8.8	2.1	1965–1995	−7	3.7	1980–1996
Tinopo	P96K2	100.50499	−3.16275	−4.1	0.8	1969–1996	−4.1	0.8	1969–1996
Siatanusa	P96J3	100.48669	−3.21588	−5.2	1.8	1954–1995	−1.5	2	1981–1996
Stupai	Sd96A1	100.67938	−3.4545	−9.5	2	1949–1995	−1.9	4.9	1981–1996
Sanding	Sd96C1	100.67683	−3.4805	−9.6	1.7	1942–1996			
Tikos	T96A1&2	102.21	−3.82	0	0.6	1966–1996		0.6	

and the Pagai islands; it is less certain across Siberut island, because all data points are on the northeastern coast. Nonetheless, contouring the Siberut data in a manner most consistent with data to the northwest and southeast yields a pronounced trenchward tilt. With the exception of one site, rates on Siberut increase from northwest to southeast from about 2 to about 14 mm yr<sup>-1</sup>.

[54] Subsidence and general trenchward tilt of the Mentawai islands is consistent with interseismic locking of the underlying megathrust [Savage, 1983]. Prawirodirdjo *et al.* [1997] used measurements of horizontal deformation from sparse GPS measurements made through the 1990s on the islands and mainland to argue that both the Mentawai and Batu islands sections of the megathrust are locked, perhaps from the trench to depths of about 50 km, beneath the middle of the strait between the islands and the mainland.

However, Sieh *et al.* [1999] and Natawidjaja *et al.* [2004] showed by forward modeling of coral data that the megathrust beneath the Batu islands slipped predominantly aseismically throughout the 20th century, despite slip of about 2.5 m on a 35- by 70-km patch beneath the islands during the M<sub>w</sub>7.7 earthquake of 1935. Aseismic slip below and trenchward of the Batu islands explains the very low rates of interseismic subsidence on the westernmost large island of the Batu group. Aseismic slip east of the islands and partial locking of the 1935 patch produces the belt of uplift east of the islands (Figure 9).

[55] The fact that the Mentawai islands are tilting and subsiding much more than the Batu islands implies that the megathrust beneath the Mentawai islands is locked to a greater degree than it is beneath the Batu group. We leave quantitative examination of this to a later paper (M. Chlieh



**Figure 9.** Map of average rates of subsidence of the Mentawai and Batu islands for the latter half of the 20th century. Contours show that, in general, rates increase southwestward toward the trench. Rates are anomalously high in the strait between Siberut and Sipora islands. The anomalously high value near 1°S is ignored in the contouring. Color coding of sites indicates the period spanned by the microatoll record. Uncertainties are  $1\sigma$ .

et al., Geodetic and paleogeodetic resolution of locked patches on the Sunda megathrust, offshore Sumatra, manuscript in preparation, 2006), because a proper treatment entails the use of GPS data, in combination with the coral data.

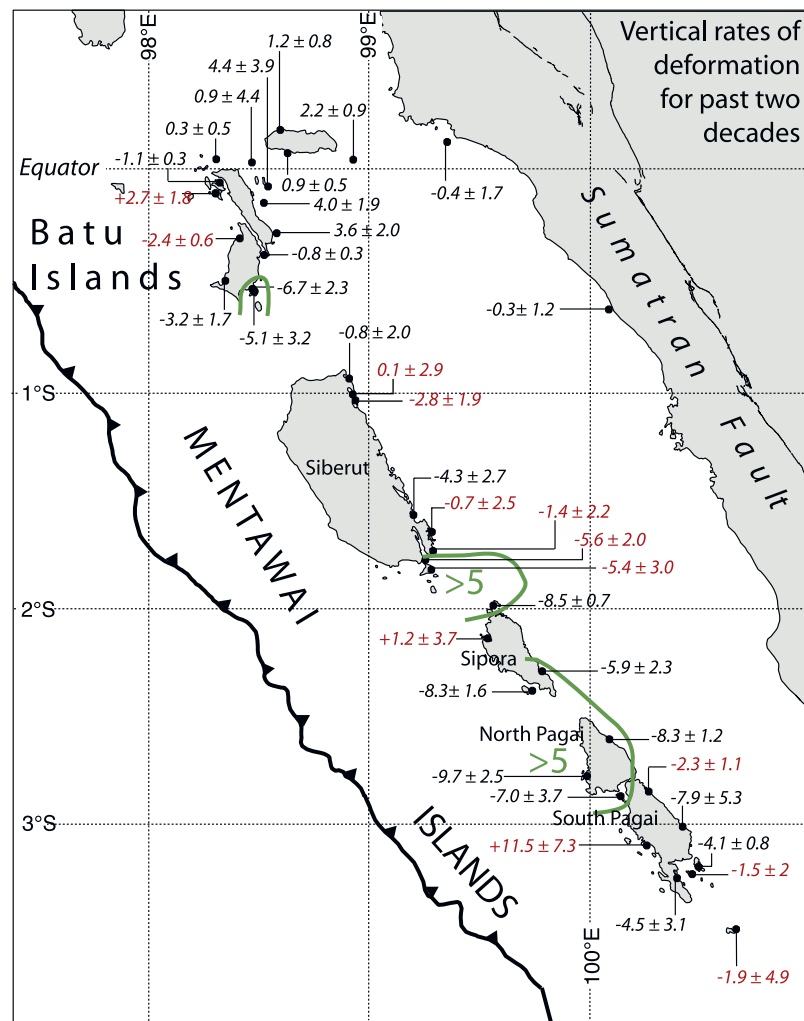
### 3.2. Slow Down in Rates Since the Mid-1980s

[56] Figure 10 illustrates rates of vertical deformation for the last two decades of the 20th century. A quick comparison of these rates with the 50-year rates in Figure 9 shows that average rates of subsidence through the 1980s and 1990s are generally slower than the 50-year average rates. The values shown in red in Figure 10 show the greatest disparity; they do not overlap the 50-year rates at the  $1\sigma$  level.

[57] In stark contrast to the average rates of the period 1950–2000, only eight sites sustained rates of subsidence greater than about  $5 \text{ mm yr}^{-1}$  between 1980 and 2000. The fast subsidence of previous decades even gave way to emergence at rates of about  $1.2$  and  $11.5 \text{ mm yr}^{-1}$  at two sites on the Mentawai coasts (Pitogat and Bulasat, respectively).

[58] One possible explanation for this lessening of subsidence rates is partial failure of the locked megathrust on localized patches beneath the islands. Complete coupling of the megathrust drags the overlying crust down at a high rate. Patchy aseismic slip within the locked patch would decrease the rate of subsidence. This is the most plausible explanation for the change from subsidence to emergence at the





**Figure 10.** Map of post-1985 average rates of subsidence of the Mentawai and Batu islands. Rates appear in red at sites where they are significantly slower than 50-year average rates. About half of these cluster around north Sipora and southern Siberut islands. For most of the Batu islands sites, there is scant evidence that rates have varied appreciably over the past half century.

Pono site in the northern Batu islands. There, the 20-year average emergence rate of about  $2.7 \text{ mm yr}^{-1}$  (Figure 10) is a long postseismic transient that followed a sudden 100-mm emergence in 1984, the year of a  $M_w$  7.2 earthquake in the region [Natawidjaja et al., 2004, Figure 12e; Rivera et al., 2002]. Seismic slip beneath the site in 1984 is the most plausible explanation for sudden uplift in 1984. Aseismic afterslip beneath the site through the following decade could explain the switch to emergence. At Mentawai sites like Pitogat and Bulasat, where a switch from subsidence to emergence began in the 1980s or early 1990s, localized aseismic slip on the megathrust also seems particularly plausible. However, if this is the cause, the subjacent patch would need to be large enough and to be slipping fast enough to more than counteract the subsidence caused by regional locking of the megathrust. This same process of patchy aseismic failure is also worth considering for Mentawai sites where submergence continued through the 1980s and 1990s, but at a lesser rate.

[59] Alternatively, lower Mentawai subsidence rates during the 1980s and 1990s might reflect permanent defor-

mation of the hanging wall block above the megathrust. Perhaps late in the seismic cycle, when accumulating stresses are highest, rocks of the hanging wall block experience most of the permanent penetrative deformation that results in uplift of the outer-arc ridge. Neotectonic growth of the Mentawai islands could be occurring at rates of a fraction of a millimeter per year [Zachariassen, 1998]. If such growth occurs in just the last 10% (~20 years) of the seismic cycle, uplift due to this process would contribute  $\sim 10 \text{ mm yr}^{-1}$  to the time series during that interval. Although this magnitude of effect would fit the observed slowing of subsidence rates, this explanation seems unlikely, given that rates of subsidence measured by cGPS in the past few years are nearly the same or even higher than the 50-year rates (Table 3). If this process were operating in the latter stages of the seismic cycle, one would expect modern cGPS rates to be far lower.

[60] The most pronounced cluster of sites of slowing subsidence is in the region of northern Sipora and southern Siberut, near the terminus of the 1833 megathrust rupture and the anomalously high rates of subsidence for the period

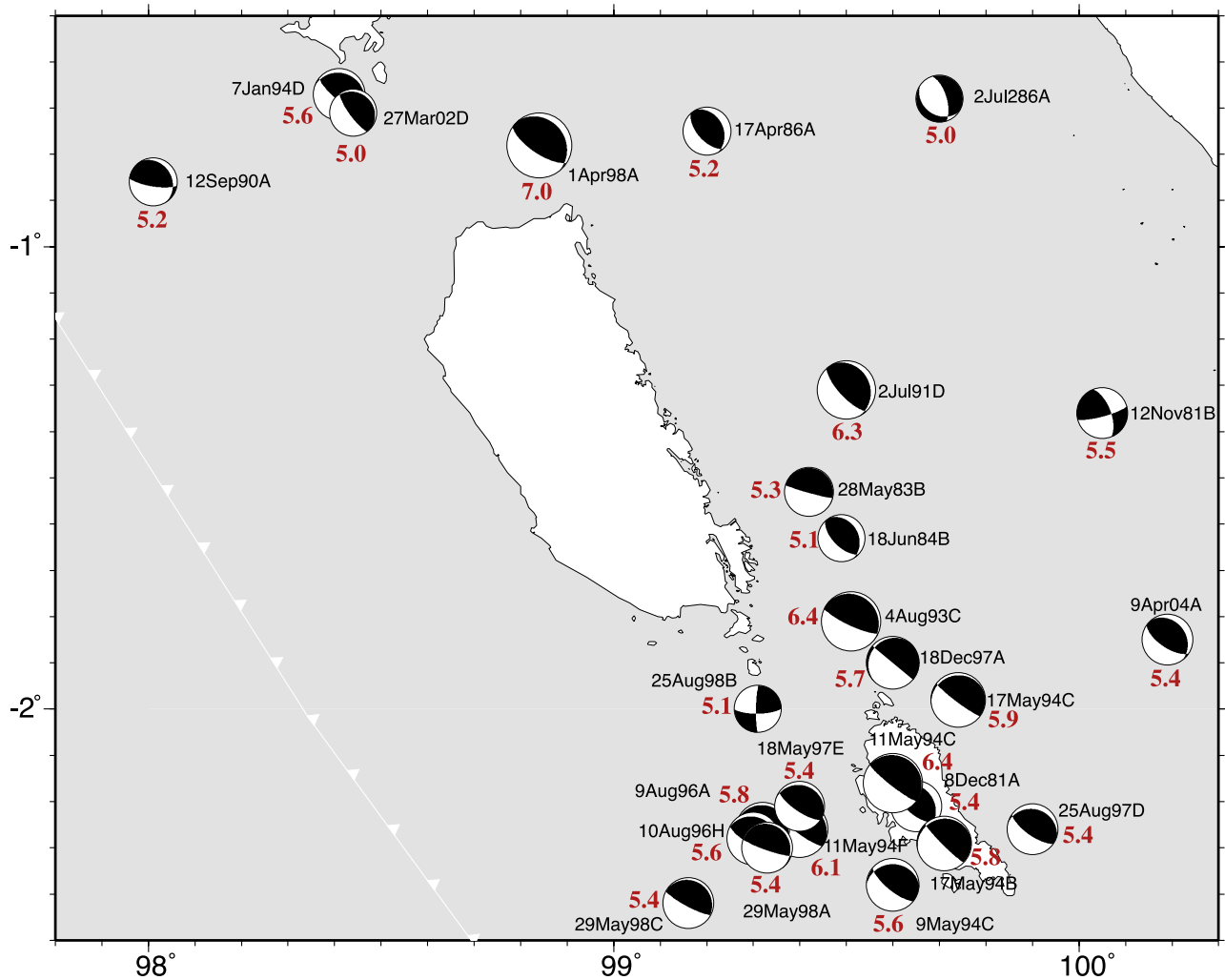
**Table 3.** Comparison of cGPS and Coral Microatoll Rates of Subsidence

cGPS Station	cGPS Rate	20-year Rate	50-year Rate	Microatoll Site
MSAI	$-9.1 \pm 1.6$	?	$-6.5 \pm 1.0$	Saibi
NGNG	$-10.0 \pm 2.5$	$-5.4 \pm 3.0$	$-14.3 \pm 3.3$	Masokut
PPNG	$-22.6 \pm 1.8$	$-8.5 \pm 0.7$	$-8.5 \pm 0.7$	Pulau Panjang
SLBU	$-15.2 \pm 2.0$	$-9.7 \pm 2.5$	$-9.7 \pm 2.5$	Silabu
PRKB	$-10.2 \pm 0.6$	$-7.9 \pm 5.3$	$-6.0 \pm 2.6$	Sibelua
BSAT	$-9.2 \pm 1.0$	$-11.5 \pm 7.3$	$-13.4 \pm 1.3$	Bulasat

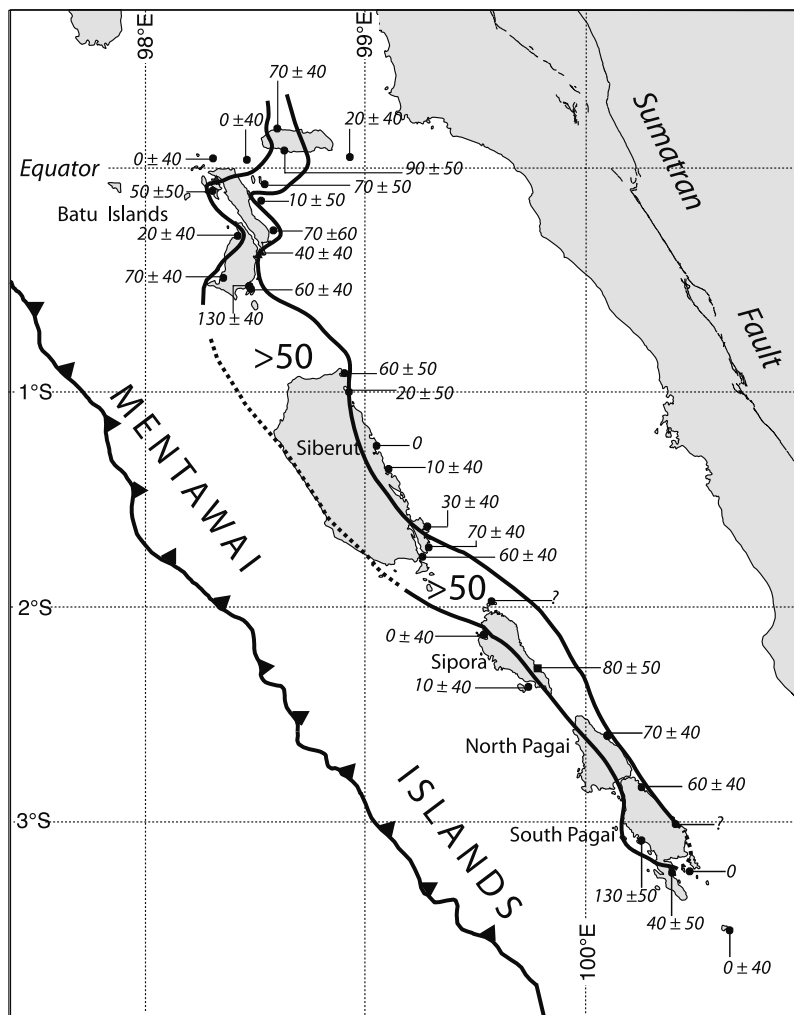
1950–2000. It may be significant that this region has been host to a very high concentration of  $M_w$  5 to 6.8 earthquakes since at least the mid-1980s (Figure 11), including a cluster of  $M > 6$  earthquakes on 10 April 2005. These earthquakes may follow from aseismic slip on the megathrust, as *Hsu et al.* [2006] have argued for aftershocks of the 2005 Nias-Simeulue earthquake. Alternatively, this clustering of moderate earthquakes could be seismic slip on patches within a regionally locked section of the megathrust. If seismic activity or aseismic slip or both have picked up on this section of the megathrust in the past couple decades, it could

be manifest as slower rates of subsidence of the overlying islands. If the section of the megathrust between Siberut and Sipora has a significant component of aseismic slip, it could explain why the northwestern terminus of the 1833 rupture [Natawidjaja et al., 2006] occurred here. When the rupture reached this section of the megathrust, accumulated stresses were too low to allow propagation of the rupture farther to the northwest.

[61] It is certainly speculation to suggest that the diminished rates of subsidence of the last 20 years of the 20th century are associated with accelerated failure of small



**Figure 11.** Map of the cluster of moderate ( $M > 5$ ) earthquakes in the region of Siberut and Sipora islands. These earthquakes may be evidence for partial decoupling of the megathrust between great earthquakes. Data are for earthquakes shallower than 100 km, between 1976 and December 2004 (from <http://www.globalcmt.org/CMTsearch.html>).



**Figure 12.** Map of emergence in about 1962  $\text{mm yr}^{-1}$  suggests a welt of minor uplift along the Mentawai and Batu islands.

patches on the locked Mentawai section of the Sunda megathrust. However, it is a hypothesis that can be tested with monitoring by a continuously recording GPS array and a seismic network.

### 3.3. Rapid Emergence/Subsidence Episodes

#### 3.3.1. The 1962 Emergence and Submergence Events

[62] HLS unconformities are rare or absent in most of the long records during the period from about 1962 to the mid-1980s. This suggests that this part of the record is dominated by a long period of accelerated subsidence at rates near or in excess of the unimpeded upward growth rates of the microatolls. Alternatively, the period could have begun with a large, subsidence event.

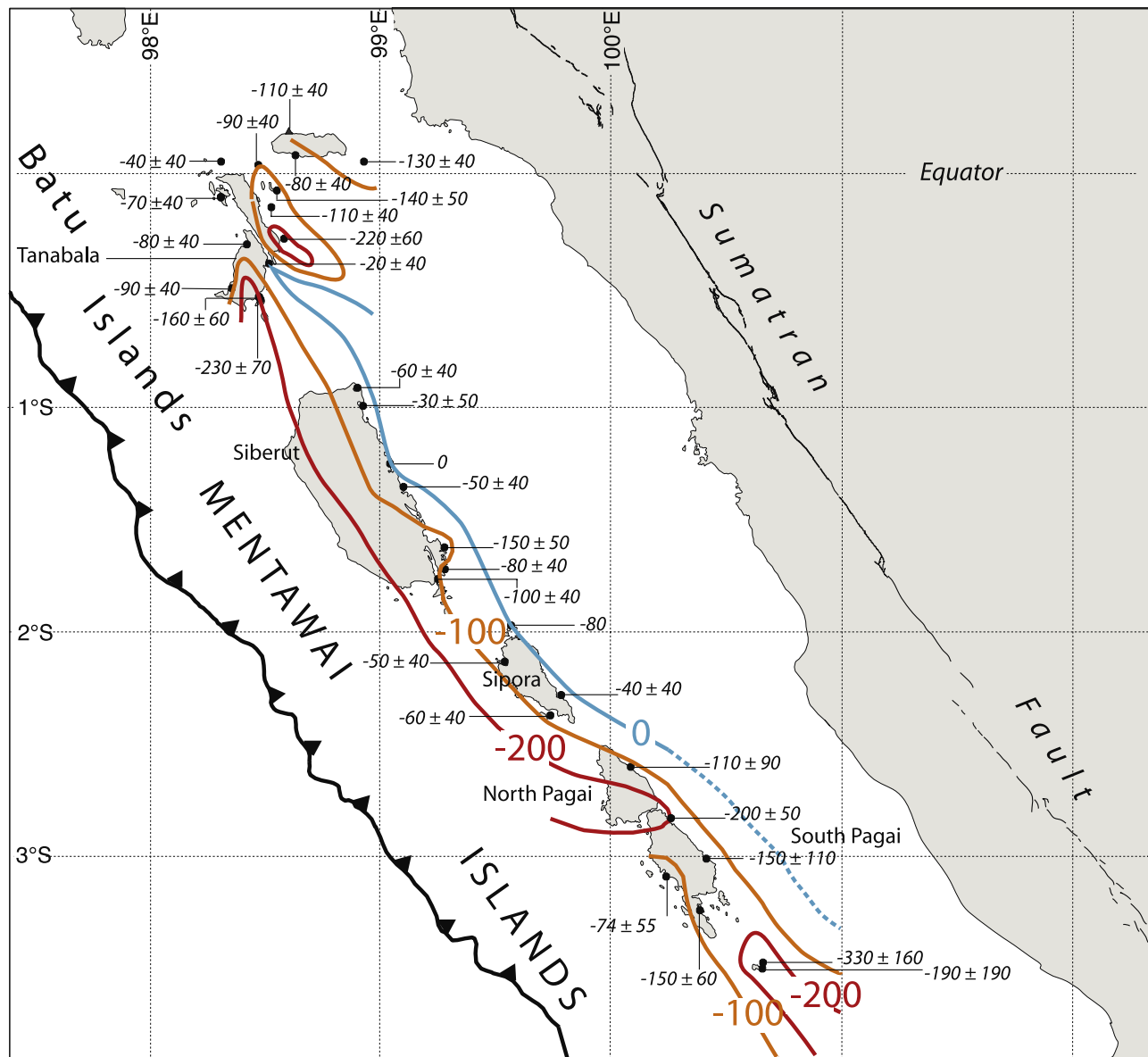
[63] In fact, many of the records indicate that this period began with a pronounced lowering of HLS followed by a larger subsidence event, both in about 1962. This episode of rapid emergence and subsidence is plausibly the same pair of events documented farther north, near the equator by Natawidjaja *et al.* [2004]. Timing of the emergence/submergence episode is very well constrained by absolute ages of coral rings of microatolls from the Batu islands at the Masin and Tofa sites (Figure 3). There the coral records

reveal that the submergence event could not have continued for more than two years beyond 1962. The record from Pitogot, where subsidence was small, confirms this timing (Figure 8n); by 1964, another HLS unconformity had formed on the microatoll there.

[64] The amount of the initial emergence in or about 1962 varies from about nil to 100 mm among the Mentawai sites. The data suggest, but by no means require, that the emergence had the form of a welt centered on the islands (Figure 12).

[65] The submergence event, later in about 1962, is constrained better, because more sites unambiguously record a period of uninhibited upward growth and the signal is larger. Along the northeastern coast of Siberut, sites subsided between zero and 150 mm (Figure 13). This range in values is nearly as great as that reported by Natawidjaja *et al.* [2004] in the Batu islands. Subsidence also occurred on Sipora and the Pagai islands. On South Pagai and on islets farther south, subsidence ranged from about 75 to 330 mm.

[66] Except on Siberut island, the pattern and magnitude of submergence is constrained by measurements on both sides of the islands. In the Batu islands, a southward plunging trough of subsidence is constrained by several



**Figure 13.** Map of submergence later in about  $1962 \text{ mm yr}^{-1}$  suggests a trough of subsidence about 70 to 100 km northeast of the trench. Maximum magnitude of subsidence is at least 230 mm.

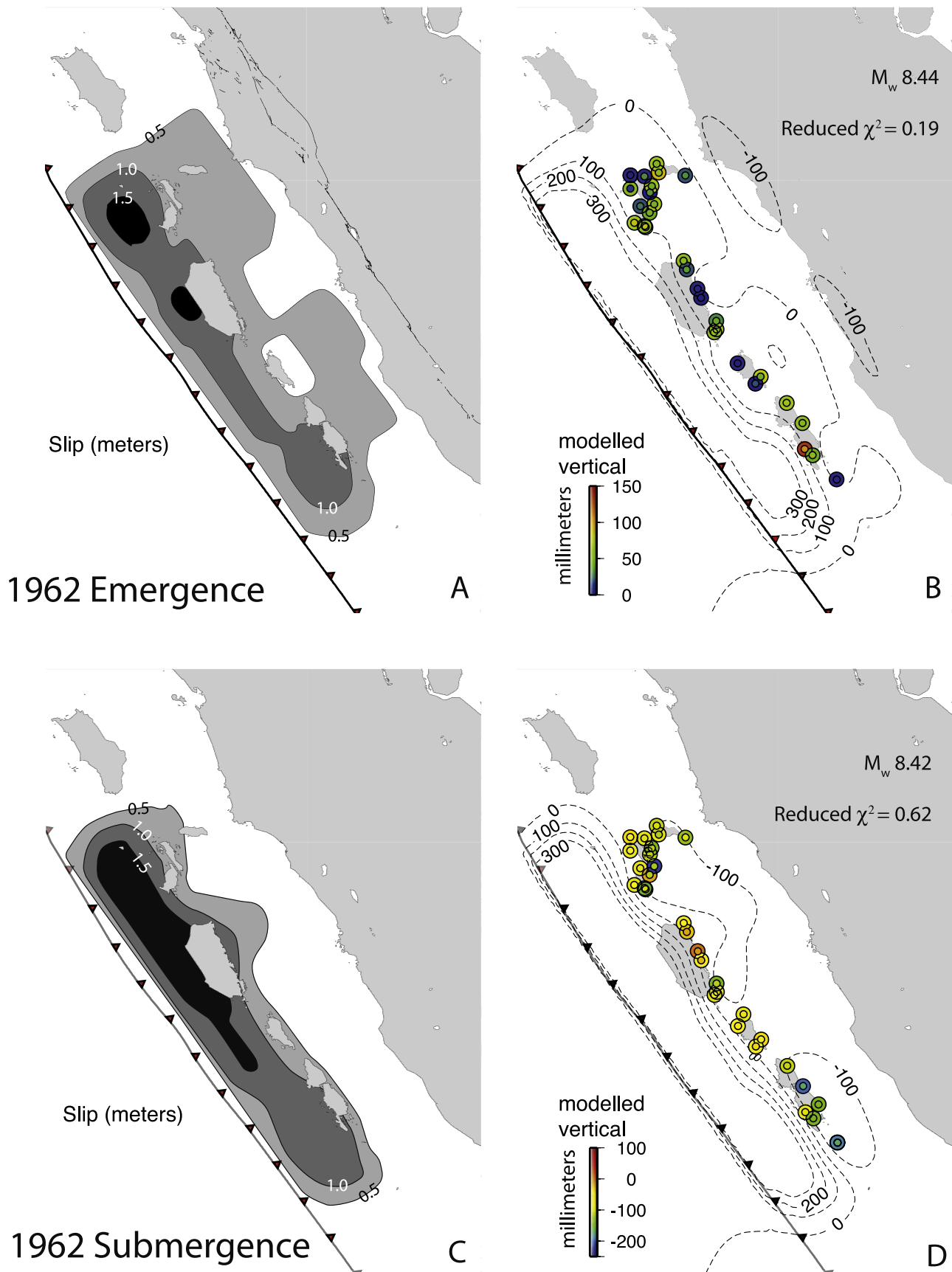
points on the large southernmost island (Tanabala). A trough, plunging about west, may also exist on South Pagai, with a maximum depth of at least 200 mm. The contours in Figure 13 give a reasonable interpretation of the overall pattern, a belt of subsidence running at least 440 km, from about the equator to at least  $3.6^\circ\text{S}$ . In detail the pattern could, of course, be significantly different, since the data are sparse and the uncertainties in magnitude commonly a large fraction of the measurement.

[67] *Natawidjaja et al.* [2004] searched for patterns of slip on the megathrust that would yield the 1962 uplift and subsidence events on the Batu islands. Basically, it appears that the events resulted from slip on patches updip, downdip and within the 1935 seismic rupture, which extended from 15 to 27 km depth. For the initial uplift event, they found that about 1.5 m of slip on three narrow patches, at 20, 28, and 40–50 km depths fit the data best. For the subsidence

event, they fit the data best with slip on two patches: 1.7 m of slip between the trench and a depth of 19 km and 1.2 m of slip between 24 and 30 km depth. Their modeling suggests, then, that aseismic failure began deeper (20 and 40–50 km) and progressed updip (19 km to the trench and 24–30 km).

[68] What we know now is that the 1962 events were not limited to the Batu islands. In fact, they extended at least 400 km farther to the southeast, with about the same amplitudes of uplift seen in the Batu islands. The large uncertainties in the data do not merit an exhaustive search for the details of slip that caused the uplift and subsidence events. Nonetheless, we have attempted to invert the data for slip on the megathrust. Figure 14 shows one of the better fits we found for each event. Figures 14b and 14d show the observed vertical deformations and the model values at each site. The colored dots represent both the data (outer colored





**Figure 14.** Megathrust slip models of the emergence and subsidence episodes of about 1962. These modeled ruptures are similar in amplitude and extent to the afterslip that occurred updip of the great Nias-Simeulue rupture of 2005, a few hundred kilometers to the northwest.

ring) and the model (inner part of the colored circle) at the same point. The more similar the color of the outer and inner portions of the dot, the better the fit of the model to the data. At many sites, the model values differ from the data values. Nonetheless, the large uncertainties in the data values (Figures 12 and 13) keep model reduced- $\chi^2$  values to less than 1.

[69] Figures 14a and 14b show patterns of slip on the megathrust for the emergence and submergence events, respectively. In both models slip on the megathrust is concentrated on a strip between the islands and the trench. The aseismic moment magnitude of both model events is  $M_w$  8.4. The principal difference between the models of the emergence and submergence events is that during the emergence event, a significant amount of the slip is deep, between the islands and the mainland.

[70] If one attempts to force all slip during the emergence event to this deeper portion, the reduced- $\chi^2$  increases to 0.69, still an acceptable value, but a worse fit than the model in Figure 14a. Regardless of the details of slip during the emergence event, the centroid of slip must be farther downdip during the emergence event than during the submergence event. Thus the emergence/submergence episode evolved at the latitude of the Mentawai islands as it did under the Batu islands, progressing from deeper slip to shallower slip [Natawidjaja *et al.*, 2004].

[71] In several respects, the 1962 episode is similar to the afterslip that occurred in the year following the 2005 Nias-Simeulue earthquake north of the equator [Hsu *et al.*, 2006]. Afterslip after the great 2005 rupture occurred updip of the seismic rupture. Likewise, slip in 1962 is concentrated updip of the great ruptures of 1797 and 1833 documented by Natawidjaja *et al.* [2006]. Both 1962 and 2005 aseismic episodes involved similar amounts of slip, a meter or two. The clear difference between the 1962 and 2005 episodes is that the former episode was not stimulated by a giant earthquake. The belt of afterslip updip of the giant 2005 earthquake rupture can be ascribed to sudden stressing of a rate-strengthening material, whereas the 1962 had no obvious trigger.

### 3.3.2. Small Emergence/Submergence Episodes of 1968, 1975, and 1984

[72] In the time series of Figure 8, three other dates stand out across the region as times of emergence followed by submergence, 1968, 1975, and 1984. All are smaller than the 1962 event. We have not produced maps of these episodes, because their small size makes the patterns of deformation less clear. None of these episodes has the geographical extent or the magnitude of vertical change of the 1962 events.

[73] The 1968 incident appears in 7 records as 20 to 90 mm of emergence followed by 60 to 300 mm of submergence. As in 1962, initial emergence is smaller than subsequent submergence. All but one of the sites are on Siberut. The episode definitely did not occur at two sites on Sipora but appears at one site south of these. Several sites south of Sipora experienced more than 100 mm of submergence in 1962, so that their coral would not have grown back up to near HLS in the few years between 1962 and 1968. Thus the 1968 emergence event could have occurred in the southern reaches of our study area but gone unrecorded as an HLS unconformity.

[74] The 1975 episode also consists of a lesser initial emergence followed by a greater submergence. It is an even smaller event, with emergences of zero to 30 mm followed by submergences of zero to 140 mm. Evidence for this pair of events is also sparse; only 7 records exist. Also, the geographic extent is even spottier than that for the 1968 events. Neither emergence nor submergence occurred on northernmost Siberut, on western Sipora, and northeastern South Pagai. As in the case of the 1968 events, many sites, however, were still recovering from the earlier submergences and would not have recorded a small HLS unconformity in 1975.

[75] The 1984 episode is like the 1975 episode in that its magnitude is very small and its geographic extent is discontinuous. Five sites clearly did not experience either emergence or submergence; four record emergence of up to 90 mm followed by up to 120 mm of submergence; three experienced between 29 and 200 mm of submergence, without a preceding emergence; and two experienced a distinct change in rates in about that year.

[76] Taken together, these events of the late 1960s, 1970s, and 1980s are smaller in amplitude and geographic distribution. Perhaps they are due to localized, small-amplitude slips on patches within the locked portion of the megathrust. Ongoing seismic and geodetic monitoring may well record similar events in the course of the next decade or two.

## 4. Summary and Conclusions

[77] Coral microatolls show that subsidence at rates from about 2 to 14 mm yr<sup>-1</sup> has predominated on the Mentawai islands over the past several decades (Figure 9). This is in stark contrast to the large, sudden uplifts that occurred during great seismic ruptures of the underlying megathrust in 1797 and 1833 [Natawidjaja *et al.*, 2004]. During these large earthquakes, the islands rose and tilted toward the mainland. In the past half century, the islands have done the opposite; they have subsided and tilted away from the mainland.

[78] The most reasonable explanation for this long-lived and rapid subsidence and trenchward tilt is that the megathrust beneath the islands is currently locked and the hanging wall block, of which the islands are a part, is being carried down with the subducting plate. The fact that rates of subsidence increase southeastward along strike suggests that the width of the locked patch increases in that direction.

[79] The widespread decrease in rates of subsidence that began in the mid-1980s (Figure 10) may be due to aseismic slip on subpatches within the locked patch during this period. This seems most plausible in the region between Siberut and Sipora islands, where seismicity has been extraordinarily high since about 1984 (Figure 11) and where the 1833 rupture appears to have terminated. If failure of patches within the otherwise locked Mentawai patch is the cause of the slowdown in subsidence rates, it is rather ominous, since the Mentawai patch of the megathrust has ruptured about every two centuries since the late 14th century [Sieh *et al.*, 2004; Sieh, 2005]. Continuous GPS measurements at stations near six of the microatoll sites yield high rates of subsidence, which suggest a recent return to the high average rates of the past 50 years (Table 3).

[80] The rapid emergence/submergence events of 1962, 1968, 1975, and 1984 likely have a tectonic cause. However, we have constrained only the largest of these, the 1962 episode, well enough to warrant an attempt at modeling. The 1962 episode appears to have resulted from aseismic slip on the Mentawai patch, with a band of highest slips ( $>1$  m), between the islands and the trench (Figure 14). The magnitude and pattern of slip during these events is similar to afterslip in the nine months following the great Nias-Simeulue earthquake of 2005.

[81] **Acknowledgments.** Many friends, colleagues, and family members provided critical support of our field efforts in 1997, 2000, 2002, and 2003. Most central to the success of the project were the dedicated efforts of Imam Suprihanto, Susi Mardia, Dudi Prayudi, Robert Taylor, and our boat crews. The hospitality, friendship, and interest of the people of the Mentawai islands have been essential to this work. Most of this research was supported by NSF grants EAR-9628301, EAR-9804732, EAR-9903301, and EAR-0208508 (to K.S.) and EAR-9628716, EAR-9903443, and EAR-0207686 (to R.L.E.), administered through the NSF tectonics and geophysics programs. A RUTI IV grant from Indonesia's Ministry of Research and Technology provided support for the final phase of data analysis in 2005. This is contribution 30 of Caltech's Tectonics Observatory.

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